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Assessing Radionuclide Contamination of Drinking Water Systems Near Nuclear Reactors

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1. Radionuclide Contamination
2. Nuclear Reactor Sites
3. Drinking Water

Abstract

Radionuclide contaminated drinking water can expose humans to unsafe levels of radiation. The goal of this project was to determine if people in communities near nuclear reactors are at greater risk for developing negative health effects than people in other communities. This was accomplished through research on the health effects of radionuclide exposure, cancer rates near reactors, and radionuclide levels in drinking waters near reactors. It was determined that proximity to reactors does not significantly increase the risk of developing cancer.

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Chapter 1: Introduction

Radioactivity is present throughout the U.S., being produced naturally and through anthropogenic means. Naturally occurring radiation can come from space in the form of cosmic rays, from decaying radioactive elements within the earth, and from radionuclides present within humans from birth. Radiation from man-made sources comes from various medical and industrial applications. Among the uses for radiation are nuclear energy (which releases radiation as a byproduct), medical purposes such as x-rays, and industrial applications such as determining the structural integrity of materials. Although radiation has many useful properties, exposure can have negative health effects in humans. Acute exposure to high levels of radiation results in radiation sickness, and prolonged exposure to low levels of radiation can lead to the development of certain cancers.

Nuclear reactors are a large contributor of radioactive waste, responsible for about 2,530 tons of highly radioactive spent nuclear fuel each year (Heaberlin, 2004). There are currently 104 active reactors in the U.S., and each of them is responsible for storing their own spent fuel. While the Department of Energy is in the process of establishing a permanent disposal site for high level radioactive waste, the site is not anticipated to be operational until 2017.

Because there is no permanent storage facility, large quantities of high level radioactive waste are stored in various locations throughout the country. For example, it was estimated that the Hanford site in Washington state was storing about 2,100 metric tons of spent nuclear fuel in 2007 (Department of Energy, 2008a). Spent fuel is normally stored in large cooling pools for a period of time, then moved to an above-ground storage bunker. During this storage time, it is possible for radioactive material to leak into the soil and possibly contaminate local groundwater supplies. If this groundwater is used as a drinking water source, people can be exposed to radionuclides.

The U.S. Environmental Protection Agency (EPA) regulates the amount of radioactivity in drinking water in order to protect public health. Current regulations specify maximum contamination limits (MCLs) for alpha emitters, beta emitters, photon radioactivity, radium, and uranium. If the amount of radioactivity in a public drinking water system exceeds the MCL, then the water system is required to notify consumers and to reduce the concentration of the radionuclides.

Given the potential health effects of radionuclide exposure, the vulnerability of water systems to radioactive waste contamination is of concern. However, it is not known if water systems in communities near nuclear reactors tend to have higher concentrations of radionuclides than those not near reactors. In addition, it is not known whether health problems associated with exposure to radiation are higher in communities near reactors compared to communities not near reactors. Therefore, the goal of our project was to determine if people living in communities near nuclear reactors are more likely to be exposed to drinking water with radionuclide concentrations above the MCLs, and if these people are at a higher risk for developing certain types of cancer than people not living near nuclear reactors.

To achieve our goal, we first examined case studies that evaluated the association or lack of association between consuming radionuclide contaminated drinking water and development of cancer. Then, we researched counties containing nuclear reactors to determine if the water systems in those counties had higher levels of radionuclides than water systems in counties not containing a nuclear reactor. Lastly, we investigated the rates of certain cancers in counties containing a nuclear reactor as compared to the national average rates for those cancers. Based on these data, we drew conclusions about the potential human health risks, if any, for drinking water systems near nuclear reactors.

Chapter 2: Background

Radioactive waste poses a potential risk to human health and to the environment. Because of this, the storage and monitoring of radioactive waste is regulated by the federal government. Nonetheless, radioactive waste can leak from storage facilities, and this can potentially contaminate local groundwater systems and possibly endanger numerous people. This chapter describes what radioactive waste is and how it can affect humans. It also examines how humans can become exposed to this waste, as well as the laws regulating radioactive waste protocol and drinking water safety.

Radioactivity

Radioactivity is a natural process in which unstable atomic nuclei, or radionuclides, release energy as alpha particles, beta particles and gamma rays. This natural process is utilized by humans to produce energy by nuclear fission and for various medical uses. However, over-exposure to radiation is known to have harmful side effects in humans, including the development of cancer (U.S. NRC, 2008b).

Radiation was discovered by Henri Becquerel in 1896 when he found that he was able to develop photographic paper using uranium. Marie and Pierre Curie worked extensively with radioactive ores in the late 1800s and were able to isolate and identify several other radioactive elements, including polonium and radium (Lawrence Berkeley National Laboratory, 2008). In 1911, Ernest Rutherford discovered that radioactive elements decay over time (Peters *et al.,* 2008).

Radioactivity is measured in several different units, corresponding to different applications of the measurement. The first type of measurement is the curie, denoted Ci (English units), or the Becquerel, denoted Bq (SI), and measures how many radioactive particles a sample is emitting per second (Radiation Emergency Assistance Center, 2008). The second type of measurement is the rad (English units) or the gray, denoted Gy (SI), and measures how much radiation energy is absorbed per unit mass of a substance (U.S. NRC, 2008c). The final type of measurement is the rem (English units) or sievert, denoted Sv (SI), and measures the effect that a dose of radiation will have on a human (Radiation Emergency Assistance Center, 2008).

Types of Radiation

Radiation exists in nature as well as being created through anthropogenic means. Radiation that is found in nature is called background radiation and can come from many sources. Cosmic rays are charged particles emitted by the sun and other stars that interact with the Earth's magnetic field and produce showers of radiation. The effect of this is greater at higher elevations, with the average dose of cosmic radiation for someone in Denver, at an elevation of 5280 ft, being 50 millirem/year while the average dose at sea level is 26 mrem/year (Princeton University, 2008). Background radiation is also produced by naturally decaying uranium in soil, as well as the decay of radioactive particles that result from the break-down of uranium, such as thorium, radium, and radon. These particles can enter drinking water sources or, in the case of radon, can be inhaled (U.S. NRC, 2008i). The amount of terrestrial radiation present depends on geographical location. In the Rocky Mountains region, people are exposed to 40 mrem/year while people along the Atlantic coast are exposed to approximately 16 mrem/year (Idaho State University, 2008). Finally, all humans have radionuclides present in their bodies since birth, such as potassium-40, carbon-14, and lead-210 (U.S. NRC, 2008i). The overall background radiation dose ranges from 15 to 140 mrem/year, depending on location (Idaho State University, 2008).

Humans are also exposed to radiation from numerous man made sources. A round trip flight from the east coast to the west coast of the U.S. will expose its passengers to an additional 5 mrem due to increased exposure to cosmic rays from the higher elevation. An x-ray procedure can expose a patient to up to 130 mrem. A CT scan to the head and body results in 1,100 mrem of exposure, and various forms of radiation therapy can expose a person to up to 10,000 mrem of radiation (Idaho State University, 2008).

The type of radiation that a radionuclide is emitting can cause some radionuclides to be more dangerous than others. A radionuclide is a radioactive atom that is identified by the properties of the nucleus, such as carbon-12. Radionuclides emit different types or forms of radiation energies. The three types of radiation energy are alpha and beta particles and gamma rays (SCDHEC, 2008). Other less prevalent forms of radiation are electron capture, positive beta decay, and internal conversion. These latter types rarely occur naturally and are usually induced under laboratory conditions.

Alpha Radiation

Alpha radiation involves the emission of alpha particles, which are the largest of any emitted particle, with a mass of about four amu. An alpha particle is comprised of two neutrons and two protons, which is the nucleus of a helium atom. Because of its large size, the alpha particle has a relatively short range and small penetrating power when compared to other forms of radiation, only penetrating a tenth of a millimeter into human skin. In addition, alpha radiation is the easiest form of radiation to block, as a tissue or piece of paper will suffice to halt its progress (Nave, 2008). Alpha emitters include americium-241, plutonium-236, uranium-238, thorium-232, radium-226, radon-222, and polonium-210. Humans are normally exposed to alpha radiation by ingesting or inhaling it, and it can cause various forms of cancer in the exposed individuals (Idaho National Engineering and Environmental Laboratory, 2008a).

Beta Radiation

Beta radiation involves the emission of beta particles, which are high energy electrons emitted from the nucleus of an atom when a neutron decays. Beta emission also includes the emission of an antineutrino for every beta particle emitted. The antineutrino is a massless and chargeless particle that alters the momentum of the nucleus after emitting a beta particle. The emission of a beta particle should cause the nucleus that emitted it to recoil in the opposite direction, due to Newton's third law of motion. However, it does not because the simultaneously emitted antineutrino balances the forces. Since a beta particle is about seven thousand times smaller in mass than an alpha particle, it is able to travel further and requires more shielding to stop, such as a sheet of aluminum (Nave, 2008). Some examples of beta emitters are tritium, cobalt-60, strontium-90, technetium-99, iodine-129 and -131, and cesium-137. Humans can be exposed to beta emitters through inhalation or ingestion, as well as through skin penetration (Idaho National Engineering and Environmental Laboratory, 2008b).

Gamma Radiation

Gamma radiation does not emit a particle as in alpha or beta radiation. Rather, a stream of electromagnetic rays is emitted from the nucleus, similar to an x-ray. Gamma radiation tends have higher energy than x-rays and is used for medical purposes because of its high penetrating power (Nave, 2008). The amount of shielding needed to impede gamma radiation is measured by how much of a given material is required to absorb half of the radiation from a given source, and is called the half-thickness. Adding another half-thickness will not stop the radiation

completely, it will only reduce it by half again and so on. The half-thickness of concrete, iron, and lead are 4.7 inches, 1.3 inches, and 0.7 inches, respectively (Fentiman *et al.*, 2008a).

Other Forms of Radiation

Electron capture occurs when a nucleus absorbs one of its orbiting electrons and emits a neutrino. Positive beta decay is essentially the opposite of beta emission in that instead of emitting an electron and an antineutrino, a positron and a neutrino are emitted. A positron is a particle that has the same mass as an electron as well as the same magnitude of charge, but with the opposite sign. Internal conversion is a process by which the energy fields of the nucleus interact with an orbital electron with sufficient energy to eject the electron from the atom (Nave, 2008). Because these forms of radiation are much less prevalent than alpha, beta, and gamma radiation, the risk of being exposed is very small. However, positive beta decay and internal conversion do have the potential to cause the same type of health effects as beta radiation.

Uses for Radiation

Radiation is useful to humans in several ways, including as a source of power, as a medical instrument, and as an industrial tool. First, radiation is used in nuclear power plants to produce energy. A heavy and unstable element, such as uranium, is bombarded with free neutrons. These neutrons attach themselves to the nucleus of the uranium atom, which causes the already unstable nucleus to split apart. This releases a large amount of energy, as well as two unstable fragments of the original nucleus. These fragments emit more free neutrons that can cause nearby uranium atoms to also undergo fission, thus producing more energy (Stern, 2008). The fragments are individual elements, and include cesium-137, strontium-90, and plutonium-239. Of these products, only the plutonium can be reused while the rest become highly radioactive waste products (U.S. NRC, 2008a). Nuclear power is used to produce energy, mainly in the U.S. and Europe. In 2006, nuclear energy accounted for 19% of the power generated in the U.S. In Lithuania and France, 69% and 78% of the countries' energy was derived from nuclear sources, respectively (World Nuclear Association, 2008).

Radiation in the medical field is used both as a diagnostic tool and as a method of treatment. An x-ray is a type of radiation that is used to diagnose broken bones and dental problems. Slightly radioactive substances can also be administered to patients to assist doctors

in diagnosing and treating certain conditions. For example, iodine-131 is used in the treatment of thyroid cancer (U.S. NRC, 2008h).

Radiation has applications in many industrial fields, from engineering to agriculture. Radiation can be used to learn the thickness of materials and to locate defects in many types of metals. Seeds can be irradiated to create hardier plants. Radiation can be a substitute for pesticides in controlling insect populations, or for chemicals used as disinfectants or preservatives (U.S. NRC, 2008h).

Radioactive Waste

Radioactive waste is the byproduct of radioactive materials, and may be defined as "any waste that emits energy as rays, waves, or streams of energetic particles" (Environmental Health Center, 2008). This radiation can be harmful to humans, and can require heavy shielding to contain (Fentiman *et al.*, 2008a).

Sources of Radioactive Waste

The main sources of radioactive waste are government utilities, industries, and institutional facilities. Radioactive waste generators include hospitals, medical schools and universities, and various industries. Other producers of radioactive waste are nuclear power reactors, the necessary fuel production facilities for the reactors, and uranium fuel conversion plants (U.S. EPA, 2008d). The following discussion provides information on radioactive waste production in the U.S.

Radioactive waste from hospitals comes mainly in the form of protective clothing and equipment used in procedures involving x-rays or chemotherapy (Fentiman *et al.*, 2008c). The volume of radioactive waste produced at hospitals is small compared to the volume of waste produced in other areas, only accounting for 1% to 2% of the total radioactive waste produced (Fentiman *et al.*, 2008b).

Medical schools and universities produce radioactive waste with similar characteristics to waste from hospitals. Much of the waste produced is in the form of protective clothing and tools that have been exposed to radiation. In addition, the actual radioactive substances used in experiments and research eventually become waste themselves. The volume of the waste produced by these institutions is about 11% of the total radioactive waste produced (Fentiman *et al.*, 2008b).

Industrial radioactive waste comprises a much larger volume (46%) than medical and research institutions (Fentiman *et al.*, 2008b). Most of the waste is in the form of protective clothing and equipment, with some actual radioactive substances that had been used as disinfectants or pesticides (U.S. NRC, 2008h).

Radioactive waste from nuclear reactors can be divided between front-end and back-end waste. Front-end waste is any waste that is produced before the nuclear reactor is run and fission occurs. This type of waste includes the byproducts of mining and processing the uranium used in the reactor as well as any protective materials and tools used in these processes (U.S. NRC, 2008a). Back-end waste is radioactive waste that is produced after the reactor has run. This waste includes the spent fuel, any waste produced from the reprocessing of spent fuel, and the protective materials and tools used (Uranium Info, 2008). The volume of waste produced from nuclear sources is about 41% of the total, but the amount of radiation produced by this waste makes up 71% of all radiation produced by waste (Fentiman *et al.*, 2008b).

Classification of Radioactive Waste

Radioactive waste is classified based on how it was produced, and is broken into four categories: high-level radioactive waste (HLW), low-level radioactive waste (LLW), uranium mill tailings, and transuranics.

High-Level Radioactive Waste (HLW)

High-level radioactive waste is produced by nuclear reactors and contains the highest level of radioactivity. After a nuclear reactor's cycle has run, the spent nuclear fuel that remains is highly radioactive. This waste is then chemically reprocessed to remove unused uranium and plutonium, which can be reused as fuel in the next cycle (DOE, 2008i). The spent nuclear fuel that remains after being reprocessed is considered to be high-level radioactive waste (U.S. NRC, 2008d). HLW is radioactive enough that standing within a few feet of a freshly spent fuel rod would result in death in about an hour (Edwards, 2008).

Low-Level Radioactive Waste (LLW)

Low-level radioactive waste is defined much more broadly than any of the other categories of waste, in that it encompasses any radioactive waste that is not classified as HLW, uranium mill tailings, or transuranics. Anything that has become contaminated by contact with a radioactive substance or has been exposed to radiation is low-level waste. Some examples

include protective clothing, tools, cleaning equipment, and tissue or animal carcasses used in laboratory work involving radiation. Because low-level waste can come from such a large variety of sources, the strength of its radioactivity also varies greatly. Some waste emits at only slightly over background radiation levels, while other waste, such as tools or equipment from inside a reactor at a nuclear power plant, is much more radioactive (U.S. NRC, 2008a). Because of this variation, low-level waste is further categorized according to its half life by the U.S. Nuclear Regulatory Comission. Class A waste must be contained for one hundred years, Class B waste must be stored for three hundred years, and Class C waste must be stored for five hundred years (Nuclear Energy Institute, 2008).

Mill Tailings and Transuranics

Radioactive waste that is classified as mill tailings is any waste that is left from the processing of ore to obtain uranium (U.S. NRC, 2008a). This uranium is then utilized by nuclear reactors in nuclear power plants. Transuranic waste is radioactive waste that contains a large concentration of elements heavier than uranium, such as neptunium, plutonium, and americium (Fentiman *et al.*, 2008c). The strength of the radioactivity of these types of waste varies depending on the amount of radioactive material present in a sample as well as its density. These wastes are much less radioactive than HLW, but can have very long half-lives and require more shielding than LLW does (Sci-Tech Encyclopedia, 2008).

Storage, Transport and Disposal of Radioactive Waste

Proper handling of radioactive waste involves three components: short-term storage, transportation, and long-term storage or final disposal. Short-term storage is used to allow radiation levels in waste to decrease to safe levels prior to transport. The waste can then be moved to a long-term storage facility or disposal facility, as detailed below.

Short-Term Storage

Both LLW and HLW are stored in seclusion until the radioactivity is decayed to safe levels for transport. This storage is typically on or near the site where the waste was produced. Since the half life of LLW is generally much shorter than HLW, the initial storage period is generally much shorter than HLW. LLW is typically stored for anywhere from a few days to a few years, depending on the half life of the waste. In contrast, HLW may have a storage period

of ten years before being considered safe enough to transport (Nuclear Energy Institute, 2008). For LLW, compaction and incineration are two techniques that are widely used to reduce the mass of low-level waste in order to make it more manageable for storage. Actual storage methods include burying the waste in lined trenches, placing the waste inside concrete canisters and burying them, or storing the waste in a below-ground vault of concrete and other shielding materials (Nuclear Energy Institute, 2008). HLW can be stored in either wet storage or dry storage. Wet storage involves storing spent fuel rods in pools of water on site. The fuel rods are adequately shielded when under at least twenty feet of water. Dry storage is used when there is no longer room to store more fuel rods in wet storage. Dry storage involves an above-ground storage cask made of metal or concrete. The spent fuel rods are placed inside and surrounded with an inert gas. This method can only be employed after the rods have spent at least a few years in wet storage (U.S. NRC, 2008g).

Transportation

The Department of Energy (DOE) has strict regulations for containers that are to be used for the transportation of HLW and LLW (DOE, 2008g). Figure 1 shows the requirements for testing containers which includes:

- a 9 m freefall on to an unyielding surface
- a puncture test allowing the container to free fall 1 m onto a steel rod 15 cm in diameter
- a 30 minute 800 all engulfing burn at 800 degrees Celsius
- submersion under 3 feet of water (for 30 minutes)

Once a permanent disposal facility is developed, the DOE intends to work with the appropriate local government agencies to develop shipping routes and routines to help increase the safety and preparedness of the transporting entities. In addition, the DOE will fund training for local officials along transportation routes to respond in the event of an accident (DOE, 2008g). While the regulations for transportation are in place, waste transportation is currently limited to shipments to long-term storage facilities, which is discussed in the next section.

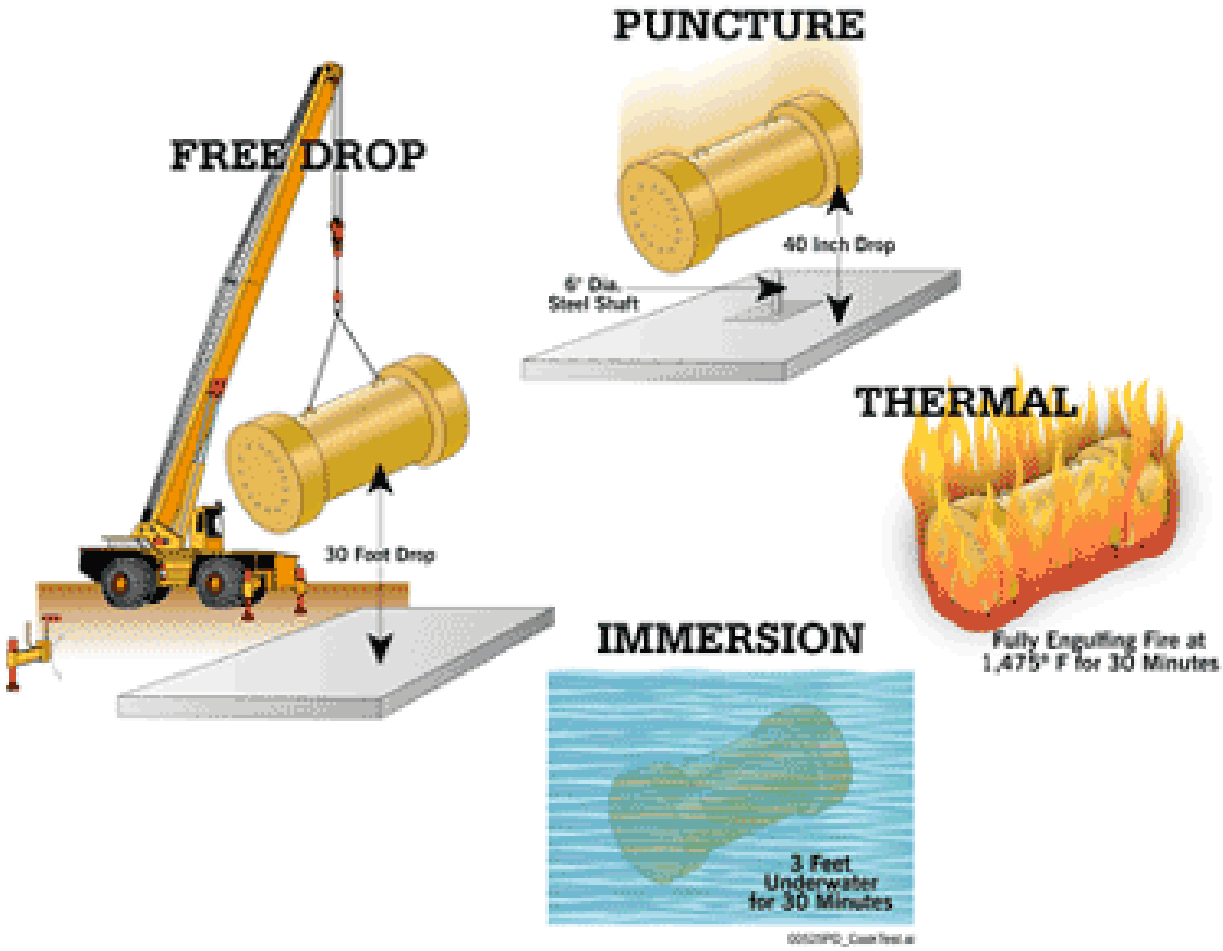

Figure 1: Container Survivability Requirements
(Source: DOE, 2008g)

Long-Term Storage

As described in the following section, there are currently no permanent disposal facilities for radioactive waste. Therefore, all waste is contained in long-term storage facilities in the U.S. As shown in Figure 2, there are 121 HLW storage facilities nationwide, distributed amongst 39 states with the most in California (9 facilities). According to an informational brief to the Minnesota House of Representatives, lack of storage space for radioactive waste is a growing problem (Helland and Bull, 2008). With no existing permanent site approved for the storage and disposal of HLW and LLW, generator sites are forced to store their wastes on site beyond the required amount of time to decay to safe levels (depending upon the type of waste) in dry casks.

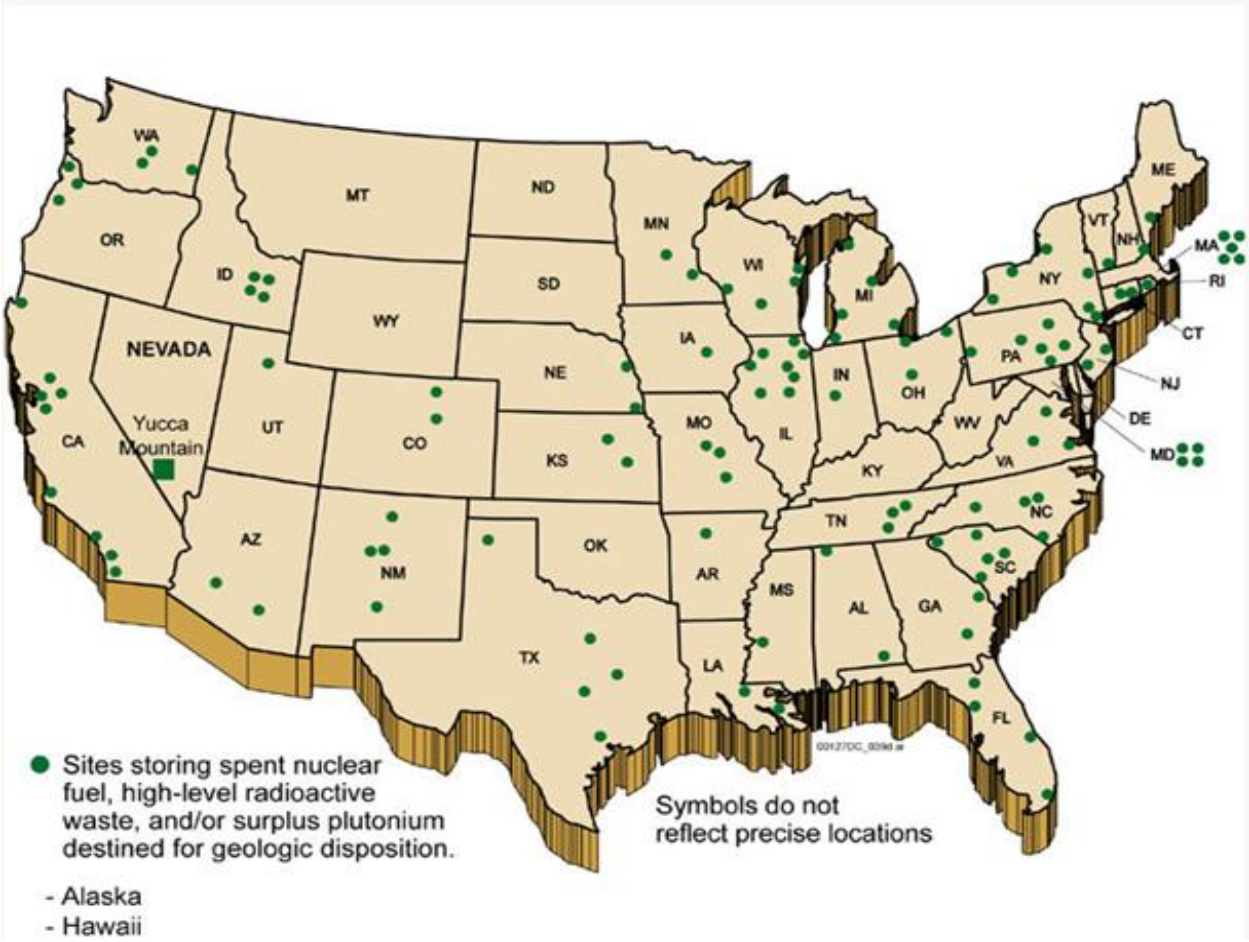

Figure 2: Radioactive Waste Storage Facilities in the U.S.
(Source: DOE, 2008h)

Disposal

According to the Low Level Radioactive Waste Policy of 1985, the states have a responsibility of disposing of LLW at a common disposal facility. In response to this, some states have developed agreements for shipping to localized facilities. For example, in Barnwell, SC, storage space can be purchased from a private storage facility where the waste is properly contained until it decays to a safe level.

The Nuclear Waste Policy Act of 1982 decreed that DOE is responsible for the creation of a permanent radioactive waste disposal site for HLW. To fulfill this requirement, the DOE began research on nine potential sites. In 1987, the Nuclear Waste Policy Act was amended by Congress, directing the DOE to narrow its research to Yucca Mountain only, located in Nye County, Nevada. As the Yucca Mountain deep geological disposal facility would have to be able to securely contain any deposited waste for 10,000 years, engineers developed a system of

natural and man-made barriers in its design to ensure that the wastes are occluded from water, geological events, and unwanted anthropogenic interferences. The only access to the repository would be from two main tunnels, and the containers would be specially designed for the facility. To prevent water from coming into contact with the wastes, the site was selected in an area where there is little rainfall. In addition, a 1,000 ft soil barrier in either vertical direction from the waste (to the surface and to the water table) was designed. Lastly, the site would also be protected by the implementation of tunnel inversions, waste packaging, and drip shields (DOE, 2008f).

The Yucca Mountain repository site would become the first major, long-term geological repository for all vitrified radioactive wastes (Knox, 2007). However, due to the anti-nuclear movement in the U.S. and efforts made by politicians, such as former senate majority leader Harry Reid, the site's construction has been repeatedly delayed (Reid, 2006).

As of January of 2008, the DOE submitted the final environmental impact statement and is waiting for licensing from the Nuclear Regulatory Commission (NRC) for the Yucca Mountain facility. During this time, the DOE continues to revise and update the design of the facility to improve containment and further meet specifications set forth by the NRC. Once approved, phased construction would begin and the repository could expect to receive waste shipments as soon as March of 2017 (Department of Energy, 2008d). As most waste would be transported to the repository via rail, the DOE has designed "transportation, aging, and disposal (TAD) containers" to meet the transportation requirements for radioactive waste. Any waste not arriving prepackaged in a TAD container would be packaged on site by the DOE (DOE, 2007).

Human Health Impacts of Radiation

Humans are exposed to background radiation in the environment every day (U.S. NRC, 2006). The health risks posed by exposure to radiation depend on the type (alpha, beta, or gamma) of radiation and its strength (Department of Energy, 2008c). A major concern is the addition of anthropogenic radiation due to the higher levels of radionuclides this radiation may contain.

Methods of Exposure

Humans can be exposed to radiation externally or internally. External exposure to radiation occurs when a person is subjected to penetrating radiation (U.S. EPA, 2008a). Beta radiation can fall under this category, but gamma radiation is the major source of external exposure due to its ability to pass through many materials, including human skin. Sources of this type of radiation include medical procedures involving radiation, such as x-rays, and cosmic rays (Department of Energy, 2008e). Internal exposure occurs when a person inhales or ingests radioactive particles (Washington State Department of Health, 2008). Beta radiation can fall under this category as well, and most exposure to alpha particles occurs in this way since they have poor penetrating power (U.S. EPA, 2007). Inhalation of radioactive materials can occur when radioactive substances are not properly shielded, or when a person is near a naturally occurring radiation source, such as radon gas (National Safety Council, 2008). Ingestion of radiation usually occurs because a food or water source is contaminated with radioactive materials. Ingestion can happen indirectly, for example, by consuming a fish from contaminated waters or a crop that was irrigated with contaminated water, which results in exposure to that radiation (U.S. EPA. 2008a).

Health Effects

Living tissue can be exposed to excessive radiation in two ways. The first is chronic exposure, in which cells are exposed to a low dosage of radiation over a long period of time. Chronic exposure to radiation tends to result in altered genetic code, leading to the mutation of cells or the development of cancer. The second type of exposure is acute, in which a high dose of radiation affects a human. This can cause Acute Radiation Syndrome (radiation sickness) and can be lethal if the dose is high enough.

Low doses of radiation are harmful to humans because they disrupt the chemical bonds inside living cells, causing changes in composition or structure. A low dose of radiation is a dose that exceeds background levels, but is not great enough to cause any measurable health effects within the first few weeks after the exposure. Any doses of ionizing radiation not exceeding 25 rads could be considered low doses (JP Laboratories, Inc., 2008). Ionizing radiation means that the radiation causes an electron to be expelled from a molecule. When this electron comes from an essential cellular molecule, or when the expelled electron directly strikes

an essential molecule, it is called direct action. This can result in the alteration of the structure or composition of the affected molecule. The majority of the damage caused by radiation is due to indirect action, however. In indirect action, the expelled electron interacts with a water molecule, causing it to ionize and become a free radical. This free radical is highly active, seeking to become stable through bonding with other molecules, which can alter the structure of important molecules within the cell (Department of Energy, 2008b).

Once a cell has been damaged by radiation, several outcomes are possible. First, the cell may repair itself and continue functioning with no risk of biophysical change. Second, the cell may die directly from the effects of the radiation. This will not typically result in any health effects unless the dose is great enough to kill many cells at once. The third outcome is that the cell survives and does not repair itself, or repairs itself incorrectly. In this case, the cell can become cancerous (U.S. NRC, 2008b). It can take ten years or more for these effects to manifest as various forms of cancer. Forty years after the atomic bomb explosions in Japan, the amount of cancer-related deaths among Japanese residents was higher than expected with Japan having 110 more incidences of cancer per 100,000 people than the worldwide average (Marugame *et al.*, 2008). Cancers associated with chronic exposure to ionizing radiation are leukemia, breast, bladder, colon, liver, lung, esophagus, ovarian, multiple myeloma, and stomach cancers (U.S. NRC, 2008b). If the damaged cell is a gamete, there is higher risk for genetic abnormalities existing in offspring (Department of Energy, 2008b).

When the dose of radiation is high enough, immediate illness can follow. This is called radiation sickness and is characterized by burns on the affected area as well as nausea, fatigue, and diarrhea. It can lead to hair loss, the development of ulcers, hemorrhaging, and inflammation and irritation of exposed skin (Perez, 2008). These symptoms can begin occurring at exposure levels as low as one gray over the whole body. At three to six grays, the mortality rate is 50% within 8 weeks without treatment, and over 6 grays, the mortality rate is 99-100% within 8 weeks without treatment (JP Laboratories, Inc. 2008). In extreme cases where the strength of the radiation is ten or more grays, death may occur within two to four weeks. Generally, those who live for the first six weeks after being exposed are no longer considered at risk for mortality (U.S. NRC, 2008f).

A pregnant woman who is exposed to radiation (either through the skin or by ingestion) can pass the radiation on to her fetus through the umbilical cord or through direct exposure if the

radioactive material settles near her abdomen. This condition is called prenatal radiation exposure and can have detrimental effects on the fetus's health depending on the stage of pregnancy. The first two to fifteen weeks of pregnancy are when the unborn baby is most vulnerable to radiation exposure, and can be harmed even at exposure levels too low for the mother to become sick. Harmful effects of prenatal radiation exposure include stunted growth, physical deformities, abnormal brain function, or a higher risk to develop cancer later in life (Centers for Disease Control and Prevention, 2008).

Pathways of Exposure

People can be exposed to radioactivity via air and water (as discussed previously). This report focuses on exposure to radioactive waste through drinking water, including both surface water and groundwater sources. A major source of radioactive waste that contaminates groundwater are storage tanks buried underground (The Groundwater Foundation, 2008). These storage tanks can corrode, crack, and develop leaks. The hazardous waste can then make its way through soil and into the groundwater. For example, the Hanford site in Southeastern Washington State is the largest nuclear waste storage area in the U.S. Waste leakage at this site was suspected as early as 1956, but was not confirmed until 1961. According to Hanson (2000), the facilities were shut down in 1987 because 67 (all single-shell) of the 177 total underground nuclear waste storage tanks were known to be leaking. This action was long overdue since the design life of single-shell storage tanks, which consist of reinforced concrete with inner carbon steel liners, is 10-20 years (Hanson, 2000).

Drinking Water Sources

When waters are contaminated by hazardous waste, they pose a threat to society since people in the U.S. rely on these waters as drinking sources. Public drinking water systems, which are regulated by the U.S. EPA, provide drinking water to 90 percent of Americans. Public drinking water systems may be publicly or privately-owned. They are defined as systems that serve at least 25 people or 15 service connections for at least 60 days per year (U.S. EPA, 2008e). The three types of drinking water systems are: Community Water Systems (CWS), Non-

Transient Non-Community Water Systems (NTNCWS), and Transient Non-Community Water Systems (TNCWS).

As of 2007, there were 52,095 CWSs in the U.S. Of these, 40,646 use groundwater as the water source. These groundwater systems serve almost 91 million people, or 32% of the U.S. population. The remaining systems (11,449) use a surface water source. Because many of these are larger systems, they serve nearly 200 million people (68% of the population). Both groundwater and surface water systems are considered in this report. Data on CWSs and other systems in the U.S. are provided in Table 1.

Table 1: Public Water System Inventory Data
(Source: U.S. EPA, 2008b)

		Water Source		
System Type		**Ground Water**	**Surface Water**	**Totals**
CWS	# systems	40,646	11,449	52,095
	Pop. served	90,549,995	195,887,109	286,437,104
	% of systems	78%	22%	100%
	% of pop	32%	68%	100%
NTNCWS	# systems	18,151	679	18,830
	Pop. served	5 ,503,282	7 87,555	6,290,837
	% of systems	96%	4%	100%
	% of pop	87%	13%	100%
TNCWS	# systems	82,851	1,878	84,729
	Pop. served	11,077,369	2 ,668,985	13,746,354
	% of systems	98%	2%	100%
	% of pop	81%	19%	100%
All	Total # systems	141,648	14,006	155,654

Regulations on Drinking Waters

This section provides a background on radionuclide drinking water regulations set forth by the Environmental Protection Agency (EPA) to help lower public health risks associated with radiation in drinking waters. In the Results chapter, we examine whether or not a correlation exists between radionuclide contamination in drinking water sources and cancer incidence.

In order to effectively protect the public, the EPA regulates public drinking water systems, including monitoring requirements and procedures to follow in the event of a particular

kind of contamination. However, the EPA does not regulate radionuclide contamination in water sources that are not utilized for drinking water systems. Rather, the EPA recommends that the drinking water regulations from the Radionuclides Final Rule be used as "reference points" (U.S. EPA, 2008f). The EPA attempts to limit public risk to a level of 1 occurrence of illness in one million people to one in ten thousand people. Risk of illness is based on health estimates for a person drinking 2 L of water a day over a period of 50 years. There are two types of regulations the EPA uses, a maximum contaminant limit (MCL) and a maximum contaminant limit goal (MCLG). A MCL is an enforceable limit where action must be taken to remediate drinking water supplies in excess of the level or punitive measures will result (the punitive measures will not be discussed). An MCLG is a definition of how much of a contaminant would exist in an ideal drinking water system, and is a goal all water systems should try to achieve.

For radionuclides in public drinking water systems, there are four classes of regulated contaminants: alpha emitters, beta/photon emitters, radon, and uranium. The EPA has set the MCL for both natural and anthropogenic radiation at 4 millirem per year for beta radiation and photon emitters, 15 pCi/L for alpha emissions, 5 pCi/L for radium isotopes, and 30 µg/L for uranium. The MCLG for each radionuclide is zero (U.S. EPA, 2000b; U.S. EPA, 2008c). However, there is some controversy on how much radiation any particular isotope delivers and there is an ongoing debate amongst the EPA and NRC over what emission rates should be used for converting a particular mass of any isotope to a corresponding radioactivity dosage. For instance, the MCL goal for uranium, set forth by the EPA in the Radionuclides Regulation Final Ruling, was 20 µg/L. It was assumed that this level would be sufficient to provide a dosage of 30 pCi/L and cause kidney damage. However, this was later amended to 30 µg/L based on updated mass to radiation conversion factors (U.S. EPA, 2008c). This controversy is due to advancements in science on estimating the approximate impact of radioisotopes on an average human body (U.S. EPA, 2000b; U.S. EPA, 2000a).

In order to determine if a drinking water system is meeting regulations, monitoring is required. The monitoring is performed by whoever has primacy of the system as determined by the EPA**.** Initially, quarterly samples are collected and tested for radionuclides. If the results are beneath the MCL, monitoring frequency may be reduced. If the results exceed the MCL on a running annual average, the site continues to be monitored quarterly until the average is beneath the MCL. If the results are >50% of the MCL but still below it, the system is tested quarterly for

one year to monitor for indications of a possible contamination problem, then moved to one sample every three years if it does not change. If the results are <50% of the MCL but detectable, the system is reduced to monitoring quarterly samples taken every six years (year-long test every six years). Lastly, if radionuclides are beneath the detectable limit, a system may be reduced to quarterly samples every nine years to maintain a safe drinking water system (U.S. EPA, 2008c).

If a system is contaminated with radionuclides above the MCL, there are suggested practices to remove the contaminants based on the type of radionuclides present. Most types of contamination can be remediated by reverse osmosis. For cases where this practice may not be financially possible or reasonable, ion exchange and lime-softening are considered as options. Remediation efforts typically fall upon the monitoring body (often a township); however, it should be noted that in the event of an industrially occurring contamination, the owner of the source of contamination may be held financially liable for remediation costs (U.S. EPA, 2000a).

In addition to monitoring and MCLs, drinking water systems must notify end users if there is a risk to their health. The EPA specifies a three tier system of notification depending upon the level and type of contamination as well as if the system operators have applied for a variance from the standard applicable laws. A tier one or "immediate notice" event is activated for severe risks to public health. The system operators or primacy party must notify the public within 24 hours via a combination of television, radio, newspapers, phone calls, and door to door notification. A tier two or "as soon as possible" event is activated when a system is found to be contaminated above the MCL but there is no immediate severe risk to the public health. In this case, primacy parties have 30 days to notify all end users by the aforementioned methods or via the postal system. A tier three or "annual notice" event is when a system contains contaminant levels that are measurable but do not exceed the MCL or if they exceed the MCL they do not pose a serious risk to public health (U.S. EPA, 2000a). The Radionuclides Final Rule requires community water systems to provide a tier 2 notice for MCL violations and a tier 3 notice for monitoring and testing procedure requirements (U.S. EPA, 2008c).

Drinking Water Variances

For systems unable to comply with an MCL because of the characteristics of its raw resources, it may be eligible for a variance which allows it to operate in violation of an MCL, but only under the condition that it does not result in an unreasonable risk to public health.

Variances are granted only for a period of time specified by the overseeing agency, which is typically the EPA. The variance is used to allow the water system to test and install removal technologies (U.S. EPA, 2008c).

Summary

As dependence on nuclear power in the U.S. continues, the possibility of radionuclides contaminating drinking water systems will also continue. Because radioactive waste is difficult to store and transport, and because there is no permanent disposal site at this time, there are multiple communities at risk for exposure to radioactivity throughout the country. For this reason, regulations have been promulgated by the EPA to ensure quality drinking water. However, violations of these regulations do occur, possibly placing communities located near nuclear reactors at greater risk for exposure to radionuclides than other communities.

Chapter 3: Methodology

The first objective of this project was to determine if a connection exists between drinking radionuclide-contaminated drinking water and an increased risk of developing cancer or other health problems in humans. Journal articles containing case studies on this topic were found in order to determine if such a connection exists. Then, the radionuclide contaminant levels that were associated with an increased risk for cancer were compared to the current MCLs established by the EPA so that recommendations could be made on whether the current MCLs are satisfactory. The second objective of this project was to determine if proximity to nuclear waste storage facilities poses a risk to human health. Research was conducted to evaluate radionuclide levels in drinking water systems near nuclear reactors to determine if people in these communities are at an elevated risk of exposure to radionuclide contaminated drinking water. In addition, cancer rates in these communities were compared to national rates.

Health Effects of Radionuclide-Contaminated Drinking Water

Case studies regarding radionuclide-contaminated drinking water and possible health effects associated with certain levels and types of contamination were obtained. Internet searches were utilized with specific keyword combinations. Searches were conducted on the following websites: googlescholar.com, sciencedirect.com, jstor.org, ebscohost.com, and cmaj.ca. On each website, the following text terms were entered in the keyword search boxes: "health effects radionuclide drinking water" and "case stud* radionuclide drink water." A publication date constraint was used to ensure that current methods for water sampling and data analysis were implemented. Only articles dated within the last 20 years (January 1, 1988 – present) were considered. The searches were also limited to full-text articles (this constraint may be specified in advanced search options) so that detailed information on the studies could be obtained. Additional articles were found using the reference lists of articles obtained via the search engines. Articles which included reference to radionuclides and contaminated water in their titles were considered relevant to this project. A total of eight articles were obtained using these methods.

For each article that was used in this project, data were compiled on the specific health condition, water quality characteristics (including radionuclide type and concentration levels), and consumption characteristics. Radionuclide concentrations were compared to drinking water

MCLs. Additional information on the study location was noted. Information on the population being studied was also gathered, such as age and gender. Lastly, statistical analyses of the data and conclusions regarding a possible correlation between radionuclide-contaminated drinking water and human health risks were reviewed.

Multiple articles for different types of health risks and radionuclides were gathered so as to compare results from different studies. The articles were divided into three groups according to the radionuclide being studied: radium, uranium and radon. Each group was evaluated based on a possible association between the radionuclide and a studied health condition. The health conditions assessed included leukemia/bone cancer, stomach cancer, and cancer of the urinary organs (kidney and bladder). In this report, leukemia and bone cancer are considered together because leukemia involves malignant blood cells that start in the bone marrow and are released into the blood stream (American Cancer Society, 2008).

Nuclear Reactor Locations

It was necessary to compile a list of reactor locations that we could further investigate. Our first task was to obtain a list of the 104 power reactor units that were in operation as of November 2007. This list was available on the U.S. NRC website (U.S. NRC, 2008e). This website lists the reactor names as well as what city and state each reactor is nearest. We used a search engine to find the county in which each reactor was located with a keyword search of the reactor name and the words "reactor county" (Google, 2008). Of the 104 reactors, there were 65 unique reactor sites. For example, Arkansas Nuclear 1 and 2 are listed as separate reactors on the NRC website, but were counted together in our analysis because they are located next to each other in the same county. Of the 65 reactor sites, the first 35 alphabetically were chosen for further analysis (see next section on community water systems), ensuring that reactors from different geographical areas of the country would be represented.

As described in the next section, radionuclide violations were compiled for the 35 selected counties. A control county was randomly selected from each state containing one or more of the 35 reactor counties. Data was compiled on these control counties for comparison purposes.

Community Water Systems

Our next task was to compile information on community water systems in the 35 chosen counties where nuclear reactors are present. We also compiled information on water systems in counties that did not have reactors for comparison purposes. Data on water systems was desired for the most recent ten year period. This timeframe was chosen because water systems that have not had a recent radionuclide violation may not have been required to test for radionuclide contamination more than once in nine years. We were unable to find this information on the U.S. EPA website, and therefore called the EPA Safe Drinking Water Hotline on February 25, 2008 (U.S. EPA, 2008g; 1-800-426-4791). The person we spoke to on the hotline directed us to the Safe Drinking Water Information System query form (U.S. EPA, 2008h). This on-line tool allows the user to choose a state and then browse violations committed by water systems in that state. The user can search by the name of the water system in question, or list all the water systems in a specified county choosing from the list. Upon selecting a water system, a list of all violations committed by that water system within the past ten years is shown. These violations include MCL violations as well as monitoring and reporting violations.

Using the Safe Drinking Water Information System query form, we obtained a list of all the water systems in each of the counties we studied. The reactor name (if applicable) as well as the county and state were recorded, along with the number of community groundwater systems, surface water systems, and total number of systems for each county. We then tabulated the systems with radionuclide violations (MCL or monitoring). Hyperlinks to the list of violations for each water system with a violation were recorded separately, along with the type of violation (MCL or not) and the population affected by the system. For systems with an MCL infraction, we recorded the type of water system (groundwater or surface water). The type of radionuclide was also noted. In this project, only MCL violations involving alpha particle activity and radium were found. If analytical results were reported for gross alpha or radium violations, these values were recorded.

After data were compiled on all counties being studied, statistical analyses were conducted to determine differences between counties. Specifically analysis of variance (ANOVA) was used to assess potential differences between control counties and counties with reactors based on the number of MCL violations and the radium concentrations. All ANOVA's were conducted at the 95% confidence level (alpha = 0.05).

Correlation Between MCL Violations and Cancer Rates

Using the state cancer profiles system available on cancer.gov (National Cancer Institute, 2008), statistical data was collected on counties with and without radionuclide MCL violations. Information was gathered on various types of cancer (stomach, leukemia, and general cancers) including: deaths per 100,000 people, the five year trend in mortality rate, and if the county was above, near or below the U.S. National Average for cancer mortality. These three cancer types were chosen because they were the ones possibly linked to radionuclide contaminated drinking waters in the case studies. These data sets were then compared to radionuclide levels for each county in an attempt to determine if a correlation exists between cancer and radionuclide contamination in drinking waters. Average values for alpha particles and radium were calculated for each county and compared to the MCLs as well.

Lastly, ANOVA was used to assess potential differences in cancer rates. For this analysis the data were grouped into radium levels of 0-5, 5-10, 10-15, and >15 pCi/L, and gross alpha levels of 0-15, 15-30, and >30 pCi/L. Groups were also separated by county category (near a reactor or control county). Cancer rate differences were assessed at the 95% confidence level (alpha = 0.05).

Chapter 4: Results and Discussion

Completion of our research into the possibility of a connection between radionuclide contaminated drinking water and development of cancer in humans, as well our investigation of radionuclide violations in water systems near nuclear reactors, has allowed us to produce a list of findings. Recommendations have been made based on these findings, and are detailed in the following chapters.

Epidemiologic Case Studies

Case study articles were reviewed and evaluated based on type of radionuclide and its concentration level in drinking water. As shown in Table 2, case studies were gathered for radium, uranium and radon in water sources. These radionuclides are mostly alpha emitters, but they also emit beta and gamma radiation (Kurttio *et al.*, 2006). Potential health risks of ingestion of these radionuclides is discussed in the following sections.

Table 2: Articles by Type of Radionuclide

Radionuclide	Health Risk Studied	Author	Year	Journal
Radium	Bladder and Kidney cancer	Kurttio *et al.*	2006	Environmental Research
	Leukemia/Bone cancer	Auvinen *et al.*	2002	Cancer Causes and Control
	Leukemia/Bone cancer	Finkelstein	1994	Canadian Medical Association Journal
	Leukemia/Bone cancer	Hoffmann *et al.*	1993	Environmental Health Perspectives
	Leukemia/Bone cancer	Fuortes *et al.*	1990	Public Health Briefs
	Stomach cancer	Auvinen *et al.*	2005	International Journal of Cancer
Uranium	Bladder and Kidney Cancer	Kurttio *et al.*	2006	Environmental Research
	Bone and Kidney Toxicity	Kurttio *et al.*	2005	Environmental Health Perspectives
	(General) Kidney Function	Kurttio *et al.*	2002	Environmental Health Perspectives
	Leukemia/Bone cancer	Auvinen *et al.*	2002	Cancer Causes and Control
	Stomach cancer	Auvinen *et al.*	2005	International Journal of Cancer
Radon	Bladder and Kidney cancer	Kurttio *et al.*	2006	Environmental Research
	Leukemia/Bone cancer	Auvinen *et al.*	2002	Cancer Causes and Control
	Stomach cancer	Auvinen *et al.*	2005	International Journal of Cancer

Radium

Several studies have been carried out to correlate the ingestion of radium through water to health risks, including leukemia/bone cancer, cancer of the urinary organs (bladder and kidneys), and stomach cancer. As discussed below, a correlation was made between radium-contaminated drinking water and leukemia/bone cancer in youths in two studies. No correlation was observed between radium-contaminated drinking water and stomach cancer, or cancer of the urinary organs.

Finkelstein (1994) studied persons in Ontario who were exposed to radium-226 and died of bone cancer and compared them to a control group who died of another cause. All study participants were under the age of 26 years. There were 283 case subjects and 285 control subjects and each were stratified by gender, age, and year of death. The demographic characteristics of the participants are shown in Table 3. Approximately 49% of case and control subjects were between the ages of 12 and 18 years. The majority of subjects were male (63%) and most deaths occurred between 1975 and 1983 (see Table 3). A total of 335 matched pairs were identified (Finkestein, 1994).

Table 3: Demographic characteristics of people in Ontario less than 26 years of age who died of bone cancer (case) or other diseases (control) from 1950 – 1983

(Source: Finkelstein, 1994)

Characteristic	Case (n = 283)	Control (n = 285)
Gender		
Male	179	171
Female	104	114
Age (yrs)		
< 12	59	60
12-18	138	142
19-25	86	83
Year of death		
1950-1964	86	87
1965-1974	94	97
1975-1983	103	101

Case and control subjects were stratified by radium concentration level. Odds ratios were calculated to determine the probability of developing bone cancer at the different concentration levels. Table 4 provides the odds ratios and their respective 90% confidence intervals (CI).

Table 4: Radium concentration in drinking water among case and control subjects
(Source: Finkelstein, 1994)

Radium concentration (Bq/L)	Control	Bone cancer cases	Odds ratio	90% CI
< 0.007	240	256	1	Reference
0.007 – 0.0299	35	26	1.44	0.88-2.35*
≥ 0.030	8	3	2.84	0.81-12.6*
Total (0.007 – 0.160)	43	29	1.58	1.01-2.50
*p = 0.045, test for trend				

Overall, 87% of the case subjects fall under the reference category of < 0.007 Bq/L radium concentration in their drinking water. In the exposed categories, the odds ratios are above unity, and there exists a trend of increasing odds ratio with increasing level of radium exposure. This suggests that the odds of developing bone cancer is higher with higher radium concentration. However, the 90% confidence interval for the odds ratios includes 1 for both exposed groups. Therefore, the individual odds ratios for the exposed categories are statistically the same as the control group. The odds ratio for the (total) exposed group is 1.58, with a 90% CI from 1.01 to 2.50 and p = 0.047. Therefore, a statistically significant correlation is observed between the risk of bone cancer and radium exposure through drinking water. According to Finkelstein (1994), when the results were adjusted for gender, age, and year of diagnosis of bone cancer, there was practically no effect on the odds ratios. Logistic regression analysis was also performed and it was found that the risk of death from bone cancer was significantly associated with the level of radium exposure (p = 0.04) (Finkelstein, 2004).

Hoffmann *et al.* (1993) also studied bone-related cancer (leukemia) in young persons (0-20 years of age) and radium-contaminated drinking water. The study was prompted by the prevalence of leukemia in two villages in the Federal State of Rheinland-Pfalz, Germany: Hoppstadten-Weiersbach and Gimbweiler. The populations of these villages were possibly

exposed to radium-226 by means of ingestion because a uranium ore processing plant was located in the nearby villages of Ellweier. The Steinaubach Brook enters the ore compound from the north and flows between dumps, and then empties into the Nahe River, which supplies the local waterworks for the two communities. To determine a possible link between the childhood leukemia and potentially contaminated drinking water, Hoffmann *et al.* (1993) compiled data on all cases of childhood malignant diseases in this region for a period of 20 years (from 1970 – 1989).

The annual ingestion of radium-226 by children aged 0-20 years was calculated based on an assumption of the daily fluid intake of the population and an average concentration of 0.36 Bq/L of radium for Hoppstadten-Weiersbach and 0.075 Bq/L for Gimbweiler. Each location was age-stratified. Table 5 shows the estimated annual and accumulated ingestion of Radium-226 for the two villages. It is estimated that an individual who had lived in Hoppstadten-Weiersbach from birth would have ingested 2,950 Bq of radium the age of 20; an individual who had lived in Gimbweiler from birth would have ingested 610 Bq by the age of 20.

Table 5: Age-specific annual ingestion of Radium-226 (Bq)
(Source: Hoffmann *et al.*, 1993)

	Annual				Accumulated (estimate)	
Age (yrs)	0 – 1	2 – 5	6 – 10	11 – 15	15	20
Hoppstadten-Weiersbach	79	131	171	197	1,965	2,950
Gimbweiler	16	27	36	41	405	610

Accumulated exposure doses in the red marrow and bone surface were calculated based on the age-specific accumulated ingestions of radium-226 through drinking water. The annual exposure doses for red marrow and bone surface for ingestion of radium-226 decreases with age. This is a result of the growth of bones and thus increased bone surface and red marrow as the body ages.

The actual radium concentrations of the drinking water of the villages of Hoppstadten-Weiersbach and Gimbweiler in past years are necessary, as well as for the surrounding areas where leukemia incidence was not prevalent. However, the study is still important for several reasons. First, the pathway on which these communities depend on their drinking water is

selectively exposing the two villages with the highest observed leukemia rates in Ellweiler. Second, radiation-specific chromosome irregularities were observed in two out of three healthy relatives of leukemia patients living in Hoppstadten-Weiersbach and Gimbweiler. Lastly, radium-226 is physiologically similar to calcium, and as a result is accumulated in the skeletal system and thus stored in close vicinity to the target cells, which are a type of red blood cells (Hoffmann *et al.*, 1993; Boutureira *et al.*, 2008).

Additional studies that assessed the effect of radium in drinking water on human health have found no link between the two. For instance, three case-cohort studies have been carried out in Finland due to the high concentrations of radionuclides found in Finnish groundwaters and wells drilled in bedrock. Since the people of Finland use these as drinking water sources, exposure to radium-226 is up to 100-100,000 times higher than in other populations (Auvinen, 2005). In each study a different health risk is evaluated. These risks include leukemia (Auvinen *et al.*, 2002), cancers of the urinary organs (Kurttio *et al.*, 2006) and stomach cancer (Auvinen *et al.*, 2005). In all three studies, the same method to obtain a study population was utilized. First, the base population was defined as the 144,627 persons born between 1900 and 1930 in Finland, and who had lived outside the municipal water supply from 1967 to 1980. Second, persons who received a diagnosis of one of the target cancers during 1981 to 1995 were used as subject cases. Third, a base cohort was defined as the 4,590 persons selected randomly from the base population and stratified by gender and age. Lastly, only those persons who had lived in residences with drinking water from drilled wells prior to 1981 were eligible for the study. Then, the study population consisted of persons who gave informed consent and activity of concentrations of water samples (Auvinen *et al.*, 2002; Auvinen *et al.*, 2005; Kurttio *et al.*, 2006). Data analysis was based on a modified proportional hazards model, with comparison of each case at date of diagnosis with subjects in the sub-cohort at risk at that time. 95% confidence intervals (CI) were also calculated.

Auvinen *et al.* (2002) obtained water samples from drilled wells for 274 sub-cohort members and 35 leukemia cases. Subjects were stratified by age and gender for analyses. The mean (average), median and interquartile range (IQR range of the middle 50% of data) for radium concentrations in drinking waters are shown in Table 6. The concentrations were comparable for leukemia cases and sub-cohort members.

Table 6: Radium-226 concentration in drinking water among cases and sub cohort
(Source: Auvinen *et al.*, 2002)

	Radium-226 concentration (Bq/L)	
	Sub-cohort	Leukemia cases
Mean	0.03	0.02
Median	0.01	0.01
IQR	0.005 – 0.02	0.005 – 0.03

Table 7 displays different ranges of concentrations to which the sub-cohorts members and the cases were exposed, as well as the Hazard ratio (HR) and 95% CI's for each group. For a radium-226 concentration of less than 0.005 Bq/L, the HR equals 1 as this is the reference level. The risk of developing leukemia is not any higher for higher concentrations of radium. In both radium groups, the confidence interval contains the value 1, which means that there is no additional risk of leukemia, and any differences between groups are likely due to chance (Bilash, 2008). According to Auvinen *et al.* (2002), adjustment for age and gender did not affect the results.

Table 7: Radium-226 concentration among cases and in the sub-cohort with hazard ratios and 95% CI of leukemia
(Source: Auvinen *et al.*, 2002)

Radium-226 concentration (Bq/L)	Sub-cohort	Leukemia cases	Hazard ratio	95% CI
< 0.005	105	13	1	Reference
0.005 – 0.02	61	8	0.77	0.30-2.01
0.03 – 1.9	108	14	0.75	0.34-1.69

Auvinen *et al.* (2005) conducted an epidemiologic study in Finland to evaluate the possible risks of stomach cancer development from radium. A total of 274 sub-cohort members and 88 stomach cancer cases were identified. Water samples from drilled wells were obtained to quantify radium levels. An adjustment for age and gender was used. The mean, median and IQR radium concentration values are listed in Table 8. The mean radium concentration in drinking water for the sub-cohort members is higher than that for the case subjects; this is also the case

regarding the median value. On average, persons without stomach cancer are exposed to a slightly higher concentration of radium in drinking water than that for persons with stomach cancer.

Table 8: Radium-226 concentration in drinking water among cases and sub cohort
(Source: Auvinen *et al.*, 2005)

	Radium-226 concentration (Bq/L)	
	Sub-cohort	Stomach cancer cases
Mean	0.03	0.024
Median	0.01	0.007
IQR	0.005 – 0.022	0.005 – 0.022

Table 9 compares the probability of developing stomach cancer to not developing stomach cancer in this study. Here, the reference concentration level is less than 0.008 Bq/L of radium-226. Higher levels of radium concentration in drinking water resulted in a decrease in risk of developing cancer. For example, for a concentration of 0.09-0.019 Bq/L, the hazard ratio is 0.37, with a 95% certainty that the HR lies between 0.19 and 0.73. This demonstrates a statistically significant decreased risk of stomach cancer associated with a higher radium concentration. However, as the concentration increases to 0.02-1.9 Bq/L, there is no evidence of an increase or decrease in risk, as the 95% CI includes the value 1. According to Auvinen *et al.* (2005), adjustment for age and gender did not affect results.

Table 9: Radium-226 concentration among cases and in the sub-cohort with the hazard ratios and 95% CI of stomach cancer
(Source: Auvinen *et al.*, 2005)

Radium-226 concentration (Bq/L)	Sub-cohort	Stomach cancer cases	Hazard ratio	95% CI
< 0.008	120	45	1	Reference
0.009 – 0.019	83	20	0.37	0.19-0.73
0.02 – 1.9	71	22	0.54	0.29-1.01

A third study on persons who utilized drinking water from drilled wells in Finland focused on bladder cancer and kidney cancer. The study population consisted of 274 reference cohort members, 61 bladder cancer cases, and 51 kidney cancer cases. The models of the bladder cancer risk included age, gender, and whether or not the person smoked. The models of kidney cancer risk included age, gender, smoking status, and body mass index (BMI) (Kurttio *et al.*, 2006). The mean, median and IQR values of radium-226 concentration are shown in Table 10. The median and IQR values were comparable for all groups. However, the mean values differed: the radium-226 concentration for bladder cancer cases was considerably higher than that for the sub-cohort and kidney cancer cases. This suggests that persons who ingest water with a radium concentration of 0.05 Bq/L or higher may be at risk of bladder cancer. To determine is this was the case, a hazard ratio was calculated for different radium concentrations (see Table 11).

Table 10: Radium-226 concentration in drinking water among cases and sub cohort
(Source: Kurttio *et al.*, 2006)

	Radium-226 concentration (Bq/L)		
	Sub-cohort	Bladder cancer cases	Kidney cancer cases
Mean	0.03	0.05	0.02
Median	0.01	0.01	0.01
IQR	0.005 – 0.02	0.005 – 0.02	0.005 – 0.03

Table 11: Radium-226 concentration among cases and in the sub-cohort with the hazard ratios and 95% CI of bladder and kidney cancer
(Source: Kurttio *et al.*, 2006)

Radium-226 concentration (Bq/L)	Reference cohort	Bladder cancer			Kidney cancer		
		Cases	Hazard ratio	95% CI	Cases	Hazard ratio	95% CI
< 0.01	159	37	1	Reference	25	1	Reference
0.01 – 0.02	69	14	1.07	0.54-2.09	13	0.53	0.25-1.16
0.03 – 1.9	46	10	0.82	0.37-1.83	13	0.70	0.30-1.65

For the concentration of 0.01-0.02 Bq/L of radium in drinking water, the hazard ratio for bladder cancer is above unity, which suggests that the risk of developing bladder cancer is higher

than that of not developing bladder cancer. However, this is inconclusive since the confidence interval contains 1, and therefore there is no statistically significant difference between this level of radium and the reference level. The HR is also not significant for higher radium levels and for the kidney cancer cases based on the confidence intervals (all of which include the value 1). There were statistically significant differences observed when the data were stratified based on smoking factors and gender. Current smokers had a higher risk of bladder cancer than nonsmokers, as indicated by a hazard ratio of 2.29 with 95% CI of 1.00 to 5.24. Women had a lower bladder cancer risk than men, which is indicated by a hazard ratio of 0.31 with 95% CI of 0.15 to 0.67. Hazard ratios lower than 0.5 and greater than 2.0 are considered relevant by statisticians in evaluation differences in risk. However, when all study participants were included, results from the three case-cohort studies in Finland demonstrated that increased radium concentrations did not increase the risk of developing bladder cancer or kidney cancer.

The last study that involved radium-contaminated drinking water took place in Iowa (Fuortes, 1990). Fifty-nine towns with single source drinking water supplies were stratified by radium content into three concentration levels. Total and acute myeloid leukemia were the health risks considered. The leukemia cases from 1969-1984, excluding 1972, that were identified included: 812,616 persons years in the high category (higher than 0.185 Bq/L), 2,055,060 persons years in the medium category (0.074 – 0.185 Bq/L) and 1,562,652 persons years in the low category (lower than 0.074 Bq/L). There was no statewide cancer surveillance in 1972. The incidence rates and the associated 95% confidence intervals for both genders were calculated for each of the three categories (see Table 12).

Table 12: Age-adjusted Incidence of Total Leukemia per 100,000 Person Years for 59 Iowa Towns (all ages), 1969-1984, excluding 1972
(Source: Fuortes, 1990)

Radium-226 concentration (Bq/L)	Cases	Rate	95% CI
< 0.074	275	10.9	7.9-13.9
0.074 – 0.185	278	11.8	8.7-14.9
> 0.185	147	12.0	7.5-16.5

The incidence rate of leukemia increases slightly as radium-concentration increases. However, if the low category group were taken as the reference, the significance of the incidence

rates for the medium and high categories can be evaluated based on the 95% confidence intervals given. For instance, the incidence rate value of 10.9 for the reference category is included in both confidence intervals for medium and high categories. Therefore, the incidence rates for these two categories are not statistically different. Fuortes (1990) also provides similar data for the incidence of acute myeloid leukemia, and found comparable results. There was no statistical evidence that age adjustment and gender specification affected the results. Thus, according to this study, radium-contaminated drinking water is not associated with leukemia incidence.

Uranium

Five studies on the ingestion of uranium through drinking water and its possible health effects on the human body were reviewed. The risks evaluated included bladder and kidney cancer, bone toxicity, general kidney function, leukemia, and stomach cancer. Two studies by Kurttio *et al.* (2002; 2005) found an association between uranium in drinking water and urinary excretion of calcium and phosphate. No connections between uranium-contaminated water and any cancer were found. The studies were all conducted in Finland and involved populations who had utilized wells drilled into bedrock, where uranium concentrations are very high (Auvinen *et al.*, 2005).

A study to evaluate possible kidney effects of chronic exposure to uranium through drinking water was reviewed (Kurttio *et al.*, 2002). The study population consisted of persons whose main drinking water sources were drilled wells for 1-34 years (average of 13 years) and who had lived in Southern Finland, where uranium concentrations are highest. A total of 325 persons represented the study population and were separated into three concentration groups: < 10 μg/L (108 persons), 10-100 μg/L (116 persons), and >100 μg/L (101 persons). Statistics were adjusted by age, gender, and body mass index (BMI). Four measures of uranium exposure were utilized. The excretion of calcium, glucose and phosphate were used as indicators of effects on the proximal tubule, a component of the renal system. The function of the proximal tubule is essentially re-absorption of the water and salts from the filtrate (a liquid from which the blood cells and blood proteins have been filtered out) into the blood of the capillaries (Britannica, 2008). In this study uranium concentrations in drinking water ranged from 0.001 to 1,920 μg/L

with a mean of 131 μg/L. The median daily intake of uranium from drinking water was 39 μg/L (see Table 13).

Table 13: Uranium exposure from drinking water and measured kidney function parameters for 325 persons (Source: Kurttio *et al.*, 2002; Kurttio *et al.*, 2003)

Parameter	Mean	Median	IQR	Range
Uranium in drinking water (μg/L)	131	28	6.2 – 135	0.001 – 1,920
Uranium in urine (ng/L)	424	78	17 – 413	1 – 5,650
Daily intake of uranium from drinking water (μg)	235	39	7.5 – 224	0.0006 – 4,128
Cumulative intake of uranium from drinking water (mg)	1,360	129	24 – 887	0.001 – 33,100
Calcium fractional excretion (%)	1.6	1.3	0.8 – 2.0	0.08 – 10
Phosphate fractional excretion (%)	27	24	19 – 33	3.6 – 177
Glucose excretion (μmol/min)	0.9	0.7	0.5 – 0.9	0.1 – 21

Table 14 shows uranium concentration and its significance with regard to fractional excretion of calcium and phosphate. Excretion of calcium, phosphate, and glucose were used as indicators of effects on proximal tubulus. The increase in outcome variable was calculated based on models assuming a normal distribution of the population. There was an increase of 9.0% phosphate excretion for the group with the high uranium concentration as compared to the reference group. There was a significant increase in calcium and phosphate excretion in persons with the highest uranium intake (300 – 1,920 μg/L) as compared to the lowest exposure group (0.001 – 1.9 μg/L), as the 95% CI was above 0. Glucose excretion (not shown) was not statistically different for uranium concentration in water or uranium intake since the 95% CI included 0. Nonetheless, a link between increased uranium exposure through drinking water and tubular dysfunction exists.

Table 14: Kidney function indicators for uranium in water
(Source: Kurttio *et al.*, 2002)

Uranium in water (μg/L)	# of persons	Calcium fractional excretion (%)		Phosphate fractional excretion (%)	
		Mean	*b*	Mean	*b*
0.001 – 1.9	37	1.5	Ref	23	Ref
2 – 9	82	1.3	-0.19 (-0.61-0.23)	27	4.6 (-1.2-10)
10 – 19	25	1.4	-0.11 (-0.67-0.46)	28	5.5 (-2.3-13)
20 – 99	83	1.5	-0.04 (-0.46-0.38)	26	2.9 (-2.9-8.7)
100 – 299	55	1.8	0.23 (-0.22-0.69)	28	5.1 (-1.2-11)
300 – 1,920	43	2.0	9.0 (2.4-16)	32	9.0 (2.4-16)
b = increase of outcome variable compared with the lowest exposure strata (Ref) with 95% CI					

The study persons with the highest uranium excretion and intake had elevated calcium and phosphate fractional excretion compared with the lowest exposure group, with daily intake of uranium ranging from 0.0006 – 4.9 μg. No association between beta-2-microglobulin in urine (indicator of proximal tubulus function) was found (Kurttio *et al.*, 2002). Also, no association between uranium exposure and creatinine clearance or urinary albumin in urine (indicators of glomerular function) was found. Results were not modified by age, gender or BMI adjustments.

To assess the possible effects of ingestion of uranium through water on bioindicators of bone turnover, Kurttio *et al.* (2005) further assessed Finnish disease rates. The study population consisted of 288 persons from 179 households. This is a subpopulation of the study conducted by Kurttio *et al.* in 2002, which consisted of 325 persons in 28 municipalities of southern Finland with at least one well that had a uranium concentration over 100 μg/L. The 288 persons were over the age of 24, were not pregnant at the time of study, and did not use equipment for removing uranium from well water. Analyses were gender-specific and adjusted for age and smoking factors for men and women, as well as adjusted for estrogen use in women.

Osteocalcin and amino-terminal propeptide of type I procollagen (P1NP) were used as indicators of bone formation. Type I collagen carboxy-terminal telopeptide (CTx) was used as an indicator of bone resorption. The characteristics of the participants and their water are included

in Table 15. The uranium concentration in water ranged from 0.001 to 1,920 μg/L overall, with 27% of the concentrations above 100 μg/L and 59% above 15 μg/L (Kurttio *et al.*, 2005). The mean concentrations for men and women were both over 100 μg/L.

Table 15: Age of study population and uranium exposure
(Source: Kurttio *et al.*, 2005)

Characteristic	Mean	Median	IQR
Men (146 participants)			
Age (yrs)	53	54	44 – 61
Duration of the use of drilled well (yrs)	13	11	6 – 20
Uranium in drinking water (μg/L)	124	28	6 – 122
Daily intake of uranium from drinking water (μg)	216	36	8 – 207
Cumulative intake of uranium from drinking water (g)	1.33	0.12	0.02 – 0.60
Uranium in urine (μg/L)	0.29	0.06	0.01 – 0.27
Women (142 participants)			
Age (yrs)	52	53	43 – 61
Duration of the use of drilled well (yrs)	13	11	6 – 19
Uranium in drinking water (μg/L)	113	26	5 – 115
Daily intake of uranium from drinking water (μg)	212	36	7 – 207
Cumulative intake of uranium from drinking water (g)	1.21	0.12	0.03 – 0.73
Uranium in urine (μg/L)	0.38	0.09	0.02 – 0.42

Since the residuals were not normally distributed, the robust regression method was utilized to analyze the data. Associations between indicators of bone turnover and uranium exposure were modeled, and regression lines and p-values were obtained (Kurttio *et al.*, 2005). For men, uranium exposure was associated with elevated levels of CTx (bone loss indicator). There was also an indication of an association between increased levels of osteocalcin (bone formation indicator) and uranium concentrations in water. However, there was no correlation between uranium exposure and levels of P1NP (bone formation indicator).

In men, increased urinary excretion of calcium tended to be associated with increased levels of CTx. Some indication was found for increased urinary excretion of phosphate with decreased levels of osteocalcin. In women, urinary excretion of neither calcium or phosphate was associated with bone markers. Therefore, uranium exposure was not associated with any indication of bone turnover (Kurttio *et al.*, 2005).

The increase of uranium exposure by ingestion of water was associated with an increase in bone resorption marker CTx for men. Smoking and age factors modified the results in men. Current smoking was associated with a decrease in osteocalcin levels, P1NP, and CTx. Age was also associated with decreased levels of the markers, until the age of 60 years. In women, estrogen use was associated with significantly decreased levels of osteocalcin, P1NP and CTx. However, no statistically significant associations with uranium exposure and bone turnover were indicated for women. This may be due to the possible masking of effects by menopause or hormone use. Other confounding factors for women included body weight changes and calcium and vitamin D supplementation (Kurttio *et al.*, 2005).

Additional research on persons drinking water in Finland have focused on uranium concentrations and the development of certain types of cancer. These studies were discussed earlier in the section on Radium, as both radium and uranium were measured. The radionuclides levels are naturally high in Finland due to composition of the bedrock of which the drinking wells exist. In a study on leukemia, water samples from drilled wells were obtained for 274 sub-cohort members and 35 leukemia cases. According to Auvinen *et al.* (2002), the distribution of water uranium concentration among leukemia cases were comparable to sub-cohort members (see Table 16).

Table 16: Uranium concentration in drinking water among cases and sub cohort
(Source: Auvinen *et al.*, 2002)

	Uranium concentration (Bq/L)	
	Sub-cohort	Leukemia cases
Mean	0.45	0.27
Median	0.06	0.08
IQR	0.01 – 0.22	0.02 – 0.19

Table 17 displays different ranges of uranium concentrations to which the sub-cohorts members and case members were exposed, as well as the Hazard ratio (HR) and 95% CI's for each. The hazard ratios for increased uranium levels were 0.80 for 0.03-0.10 Bq/L, and 0.89 for 0.11-21 Bq/L. However, the 95% confidence intervals include 1, indicating no statistically significant association between exposure to uranium in drinking water and the risk of leukemia.

Table 17: Uranium concentration among cases and in the sub-cohort with the hazard ratios and 95% CI of leukemia
(Source: Auvinen *et al.*, 2002)

Uranium concentration (Bq/L)	Sub-cohort	Leukemia cases	Hazard ratio	95% CI
≤ 0.02	77	7	1	Reference
0.03 – 0.10	81	12	0.80	0.30-2.14
0.11 – 21	116	16	0.89	0.38-2.11

In a study of stomach cancer, a total of 274 sub-cohort members and 88 stomach cancer cases were identified and water samples from drilled wells were obtained (Auvinen *et al.*, 2005). The mean, median and IQR uranium concentration values are listed in Table 18. The mean uranium concentration in drinking water for the sub-cohort members is higher than that for the case subjects; this was also the case for radium values in this study. However, the medians are the same for the cases and sub-cohort members. The IQR is wider for the control group, which my indicate more variation than for the cases.

Table 18: Uranium concentration in drinking water among cases and sub cohort
(Source: Auvinen *et al.*, 2005)

	Uranium concentration (Bq/L)	
	Sub-cohort	Stomach cancer cases
Mean	0.45	0.21
Median	0.07	0.07
IQR	0.01 – 0.23	0.02 – 0.19

Table 19 compares the hazard ratio for developing stomach cancer based on uranium concentration. In general, the hazard ratios for uranium concentrations of 0.065 Bq/L and above

are low. For example, for a concentration of 0.21 – 21 Bq/L, the hazard ratio is 0.69, with a 95% CI of 0.37 to 1.27. Therefore there is no change in risk from the reference level with uranium exposure through drinking water.

Table 19: Uranium concentration among cases and in the sub-cohort with the hazard ratios and 95% CI of stomach cancer
(Source: Auvinen *et al.*, 2005)

Uranium concentration (Bq/L)	Sub-cohort	Stomach cancer cases	Hazard ratio	95% CI
≤ 0.065	140	43	1	Reference
0.065 – 0.2	61	23	0.58	0.29-1.15
0.21 – 21	73	21	0.69	0.37-1.27

Kurttio *et al.* (2006) studied the risk of cancers of the urinary organs and a possible link to total uranium concentrations (including isotopes uranium-234, -235 and -238). The study population consisted of 274 reference cohort members, 61 bladder cancer cases, and 51 kidney cancer cases. The mean, median and IQR values of total uranium concentration are shown in Table 20. The uranium concentrations in drilled wells used by bladder or kidney cancer cases and reference cohort members were similar. The median values for all groups and the IQR values for the cases are comparable. However, the mean uranium concentration for sub-cohort members is considerably higher than that for the cancer cases. This suggests that a decrease in uranium intake through water is linked to a risk of developing bladder or kidney cancer.

Table 20: Uranium concentration in drinking water among cases and sub cohort
(Source: Kurttio *et al.*, 2006)

	Uranium concentration (Bq/L)		
	Reference cohort	Bladder cancer cases	Kidney cancer cases
Mean	0.45	0.28	0.35
Median	0.06	0.08	0.07
IQR	0.01 – 0.23	0.02 – 0.17	0.02 – 0.18

For the concentration of 0.06 – 0.19 Bq/L of uranium in drinking water, the hazard ratios for bladder and kidney cancer are above unity, which suggests that the risk of developing either of these cancers is higher than that of not developing them (see Table 21). However, the confidence interval contains 1 for both cancer case groups, so no increased risk of bladder or kidney cancer is associated with these levels of uranium concentration. The HR is also not statistically different from the reference level for higher uranium levels for either type of cancer due to the nature of the confidence intervals (all of which include the value 1).

Table 21: Uranium concentration among cases and in the sub-cohort with the hazard ratios and 95% CI of bladder and kidney cancer
(Source: Kurttio *et al.*, 2006)

Uranium concentration (Bq/L)	Reference cohort	Bladder cancer			Kidney cancer		
		Cases	Hazard ratio	95% CI	Cases	Hazard ratio	95% CI
< 0.06	136	27	1	Reference	23	1	Reference
0.06 – 0.19	62	19	1.56	0.73-3.48	16	1.04	0.49-2.22
0.2 – 21	76	15	0.90	0.41-1.98	12	0.74	0.33-1.66

In all three case-cohort studies where the study population received its drinking water from drilled wells in Finnish bedrock, where high uranium-concentrations exist, there was no evidence of these concentrations affecting the risks involved. A possible link between radon concentration in Finnish groundwaters and bladder and kidney cancer, leukemia, and stomach cancer is discussed next.

Radon

The case-cohort studies on populations in Finland with high concentrations of radioactivity in their drinking water wells, as previously discussed in the sections on radium and uranium, were reviewed based on radon contamination. According to Auvinen *et al.* (2005), the highest organ dose from ingested radon is to the stomach, which receives over 90% of the total effective dose. In this study on stomach cancer, the study population consisted of 274 sub-cohort members and 88 stomach cancer cases. The mean, median and IQR radon concentration values are listed in Table 22. The radon concentration of 1000 Bq/L was exceeded by 7% (6 subjects) of

the stomach cancer cases and by 8% (23 subjects) of the sub-cohort members (Auvinen *et al.*, 2005).

Table 22: Radon concentration in drinking water among cases and sub cohort
(Source: Auvinen *et al.*, 2005)

	Radon concentration (Bq/L)	
	Sub-cohort	Stomach cancer cases
Mean	320	310
Median	130	130
IQR	40 – 340	30 – 240

The hazard ratios for stomach cancer based on radon concentration are shown in Table 23. The hazard ratios for radon concentrations of 130 – 15,000 Bq/L indicate that there is a possible decreased risk of stomach cancer development associated with an increase in radon exposure through drinking water. The 95% confidence interval for the range 130 – 299 Bq/L includes 1; therefore, there is no statistically different risk associated with these levels. The CI for the highest radon concentration range is below 1 and it may be considered statistically significant. Statisticians would prefer an HR outside of the values 0.5 and 2.0 to indicate a meaningful statistical difference (Bilash, 2008). These data indicate that there is no increased risk of stomach cancer associated with radon-contaminated drinking water up to 299 Bq/L, and a slight decrease in risk for radon concentrations from 300-15,000 Bq/L.

Table 23: Radon concentration among cases and in the sub-cohort with the hazard ratios and 95% CI of stomach cancer
(Source: Auvinen *et al.*, 2005)

Radon concentration (Bq/L)	Sub-cohort	Stomach cancer cases	Hazard ratio	95% CI
< 130	139	46	1	Reference
130 – 299	63	22	0.54	0.25-1.18
300 – 15,000	72	19	0.48	0.25-0.94

In the other case-cohort study of leukemia risk, a total of 274 sub-cohort members and 35 leukemia cases represented the study population (Auvinen *et al.*, 2002). The mean, median and

IQR radon concentration values for this study are listed in Table 24. The mean and median radon concentrations in the well waters is higher for the control group than that for the leukemia cases.

Table 24: Radon concentration in drinking water among cases and sub cohort
(Source: Auvinen *et al.*, 2002)

	Radon concentration (Bq/L)	
	Sub-cohort	Leukemia cases
Mean	320	290
Median	130	80
IQR	40 – 340	30 – 320

The hazard ratios for different ranges of radon concentrations with the associated 95% confidence intervals are given in Table 25. The hazard ratios for concentrations outside of the reference group are less than unity. However, since the 95% CI includes the value 1 in both concentration groups, the HR's are not statistically different for the radon concentration groups. Thus there is no increased risk of leukemia associated with radon concentrations from 300 to 15,000 Bq/L in drinking water.

Table 25: Radon concentration among cases and in the sub-cohort with the hazard ratios and 95% CI of leukemia
(Source: Auvinen *et al.*, 2002)

Radon concentration (Bq/L)	Sub-cohort	Leukemia cases	Hazard ratio	95% CI
< 300	202	25	1	Reference
300 – 999	49	8	0.91	0.36-2.31
1,000 – 15,000	23	2	0.73	0.16-3.28

The study to evaluate a possible link between well water radioactivity and risk of bladder and kidney cancers measured radon concentrations of water samples for 274 reference cohort members, 79 bladder cancer cases and 65 kidney cancer cases, as described in the sections on radium and uranium (Kurttio et al., 2006). The mean, median and IQR values of total uranium concentration are shown in Table 26.

Table 26: Radon concentration in drinking water among cases and sub cohort
(Source: Kurttio *et al.*, 2006)

	Radon concentration (Bq/L)		
	Reference cohort	Bladder cancer cases	Kidney cancer cases
Mean	321	556	438
Median	130	170	140
IQR	39 – 340	34 – 550	49 – 350

The radon concentrations for the cases are higher than that for the reference cohort, which suggests that persons exposed to higher levels of radon through ingestion of water are more susceptible to developing cancer of the urinary organs, especially bladder cancer with a mean concentration of 556 Bq/L and median value 170 Bq/L. Hazard ratios and the corresponding 95% confidence intervals are shown in Table 27.

Table 27: Radon concentration among cases and in the sub-cohort with the hazard ratios and 95% CI of bladder and kidney cancer
(Source: Kurttio *et al.*, 2006)

Radon concentration (Bq/L)	Reference cohort	Bladder cancer			Kidney cancer		
		Cases	Hazard ratio	95% CI	Cases	Hazard ratio	95% CI
< 130	139	28	1	Reference	25	1	Reference
130 – 399	73	13	0.67	0.31-1.44	14	0.64	0.30-1.38
400 – 19,000	62	20	1.34	0.66-2.72	12	0.70	0.29-1.67

For the concentration of 130 – 399 Bq/L, the hazard ratios are less than unity; however, the associated CI's include the reference HR of 1. This indicates that there is no difference in risk of bladder or kidney cancer development associated with radon concentrations in this range compared to the control. The same is true for the highest measured levels and its possible link to kidney cancer. The HR for bladder cancer at levels of 400 – 19,000 Bq/L is 1.34, however, the corresponding CI includes the reference value of 1. There is no observed increased or decreased risk of bladder or kidney cancer with radon exposure through drinking water.

Summary of Case Studies

Case studies found in epidemiologic journals were reviewed to evaluate the possible health risks associated with radionuclide-contaminated drinking water. The radionuclides that were researched in these studies were radium, uranium and radon.

Finkelstein (1994) observed a link between radium and bone cancer for persons under 26 years of age in Ontario when comparing all study participants with drinking water radium levels $\geq$ 0.007 Bq/L. The Canadian target concentration is 0.10 Bq/L. The radium concentrations at which a correlation is observed is much lower than the Canadian limit. However, the hazard ratio confidence interval was 1.01 to 2.50, indicating a minor increase in cancer risk.

Hoffmann (1993) suggests that there exists a significant pathway of exposure to radium-226 through drinking water for the population of Ellweiler in southwestern Germany. The people of Hoppstadten-Weiersbach and Gimbweiler are at high risk of exposure since these villages are located within a 5 kilometer radius of a uranium processing plant. These locations were chosen based on observed childhood leukemia incidences in these areas. Hoffmann *et al.* (1993) compared the estimated radium-226 concentration to 0.00413 Bq/L, the average level in Germany. The estimated radium-226 concentrations of 0.360 Bq/L and 0.075 Bq/L in Hoppstadten-Weiersbach and Gimbweiler, respectively, are over 18 times larger than the average. In contrast, there was no statistical evidence to show any additional risk of leukemia for radium concentration levels from 0.005-1.9 Bq/L (Auvinen *et al.*, 2002) or levels from 0.074-0.185 Bq/L (Fuortes *et al.*, 1990). There was no evidence of a correlation between radium contaminated drinking water and cancer of the stomach (Auvinen *et al.*, 2005), bladder or kidneys (Kurttio *et al.*, 2006).

Risks associated with uranium contaminated drinking water regarding bone turnover and kidney function in adults were found. Kurttio *et al.* (2005) found that chronic uranium exposure indicated by uranium level in drinking water and uranium intake tended to be associated with the increased levels of the bone resorption marker CTx and to a lesser degree of the bone formation marker osteocalcin in men, which may indicate that an association between increased bone turnover and exposure to uranium through drinking water exists. In contrast, no statistically significant associations with uranium-contaminated drinking water and measured bone turnover markers were observed in women. Data was not stratified by levels of uranium concentration. Therefore, Kurttio *et al.* (2005) did not make comparisons to drinking levels.

Kurttio *et al.* (2002) found that increased uranium exposure through drinking water was associated with tubular function. The indicators of the effects on proximal tubulus for the final analysis were phosphate and calcium. Significant increases in phosphate and calcium fractional excretions were linked to high uranium intake and excretion through the urine. Kurttio *et al.* (2002) stratified the concentration of uranium with a reference level of 0.001 – 1.9 μg/L since the World Health Organization (WHO) has proposed a guideline value of 2 μg/L for uranium in drinking water. There was a statistically significant increase in phosphate fractional excretion for drinking water with uranium concentration > 300 μg/L relative to < 2 μg/L. Therefore, there is an association between uranium concentrations above the WHO guideline and bone turnover. There was no statistically significant difference in leukemia (Auvinen *et al.*, 2002), stomach (Auvinen *et al.*, 2005), bladder or kidney cancer (Kurttio *et al.*, 2006) risk based on uranium concentration levels up to 21 Bq/L in drinking water.

Auvinen *et al.* did not observe an association between radon concentrations of 130 to 15,000 Bq/L in drinking water and stomach cancer (2005) or 300-15000 Bq/L and leukemia (2002). There was no statistical evidence of risk for bladder or kidney cancer for radon concentrations of < 19,000 Bq/L in drinking water (Kurttio *et al.*, 2006).

Table 28 shows the summary results for each study grouped by radionuclide and the corresponding U.S. EPA MCL. Finkelstein (1994) observed an increase in risk of bone cancer for radium concentrations of ≥ 0.007 Bq/L in drinking water. The U.S. EPA MCL of 0.185 Bq/L is over 25 times larger than this level. Hoffmann *et al.* (1993) estimated that the persons of Hoppstadten-Weiersbach and Gimbweiler in Germany were drinking water with radium concentrations of 0.360 Bq/L and 0.075 Bq/L, respectively. The former concentration exceeds the U.S. EPA MCL of 0.185 Bq/L for radium. There was a correlation between these high levels and incidence of leukemia in persons aged 0 – 20 years. Therefore, if the radium level of 0.075 Bq/L does contribute to the risk of childhood leukemia, then the MCL should be reevaluated. However, there is statistical evidence that no additional risk of leukemia is associated with radium concentrations in drinking water above the U.S. EPA MCL (Fuortes *et al.*, 1990). Similarly, there is no additional risk of leukemia (Auvinen *et al.*, 2002), stomach cancer (Auvinen *et al.*, 2005) or bladder or kidney cancer (Kurttio *et al.*, 2006) for radium concentrations up to 1.90 Bq/L.

Table 28: Summary of radionuclides concentration levels and potential associated health risks

Radionuclide	U.S. EPA MCL	Case cohort study levels	Case cohort study results	Reference
Radium	5 pCi/L = 0.185 Bq/L	0.007 – 0.016 Bq/L	Increased risk of bone cancer for persons <25 years of age	Finkelstein, 1994
		0.075 Bq/L	Increased risk of leukemia for persons <20 years of age	Hoffmann *et al.*, 1993
		0.005-1.90 Bq/L	No additional risk of leukemia	Auvinen *et al.*, 2002
		0.009-1.90 Bq/L	No additional risk of stomach cancer	Auvinen *et al.*, 2005
		0.01-1.90 Bq/L	No additional risk of bladder or kidney cancer	Kurttio *et al.*, 2006
		0.074-0.185	No additional risk of leukemia	Fuortes *et al.*, 1990
Uranium	30 pCi/L = 1.11 Bq/L	300 – 1,920 μg/L	Increased risk of tubular dysfunction for persons >15 years of age	Kurttio *et al.*, 2002
		No concentrations ranges available	Increased bone turnover in men; no additional risk for women	Kurttio *et al.*, 2005
		0.03-21 Bq/L	No additional risk of leukemia	Auvinen *et al.*, 2002
		0.065-21 Bq/L	No additional risk of stomach cancer	Auvinen *et al.*, 2005
		0.06-21 Bq/L	No additional risk of bladder or kidney cancer	Kurttio *et al.*, 2006
Radon	15 pCi/L = 0.556 Bq/L	130-15,000 Bq/L	No risk of stomach cancer	Auvinen *et al.*, 2005
		300-15,000 Bq/L	No additional risk of leukemia	Auvinen *et al.*, 2002
		130-19,000 Bq/L	No additional risk of bladder or kidney cancer	Kurttio *et al.*, 2006

Kurttio *et al.* (2002) observed an increase in risk of tubular dysfunction in the kidneys for a uranium concentration ranging from 300 to 1,920 μg/L, which suggests that the U.S. EPA MCL of 20 μg/L is acceptable. In contrast, there was no evidence of additional risk for

glomerular dysfunction at these levels. Kurttio *et al.* (2005) also found some evidence for an association between increased bone turnover and uranium concentration in drinking water among men. However, the concentrations levels were not stratified. Thus, no comparison between radium drinking water contamination levels and the U.S. EPA MCL was made for this study. Finally, there was no additional risk of leukemia (Auvinen *et al.*, 2002), stomach cancer (Auvinen *et al.*, 2005), or bladder or kidney cancer (Kurttio *et al.*, 2006) associated with uranium concentrations at or below the U.S. EPA MCL (< 21 μg/L) (see Table 28). Therefore, the U.S. EPA MCL of 20 μg/L for uranium is safe.

For radon, there was no evidence of risk of stomach cancer (Auvinen *et al.*, 2005) for concentration of 130-15000 Bq/L or leukemia (Auvinen *et al.*, 2002) for concentrations of 300-15,000 Bq/L. Similarly, there was no evidence of risk of bladder or kidney cancer (Kurttio *et al.*, 2006) for concentrations of 300-19,000 Bq/L (see Table 28). Therefore, the U.S. EPA MCL of 0.556 Bq/L for radon is safe.

Nuclear Reactor Locations

The U.S. NRC (2008e) lists 104 active nuclear reactors, as shown in Figure 3. 32 states contain a nuclear reactor, with Illinois having the most at 13. Pennsylvania contains 9 reactors, and South Carolina contains 7. Numerous states had only one reactor, including Washington, Kansas, Iowa, Missouri, Mississippi, Maine, Vermont, Massachusetts, and Maryland. The majority of the reactors are located on the east coast as well as the eastern part of the Midwest. Many states in the Mountain Time Zone have no reactors, nor do Alaska and Hawaii.

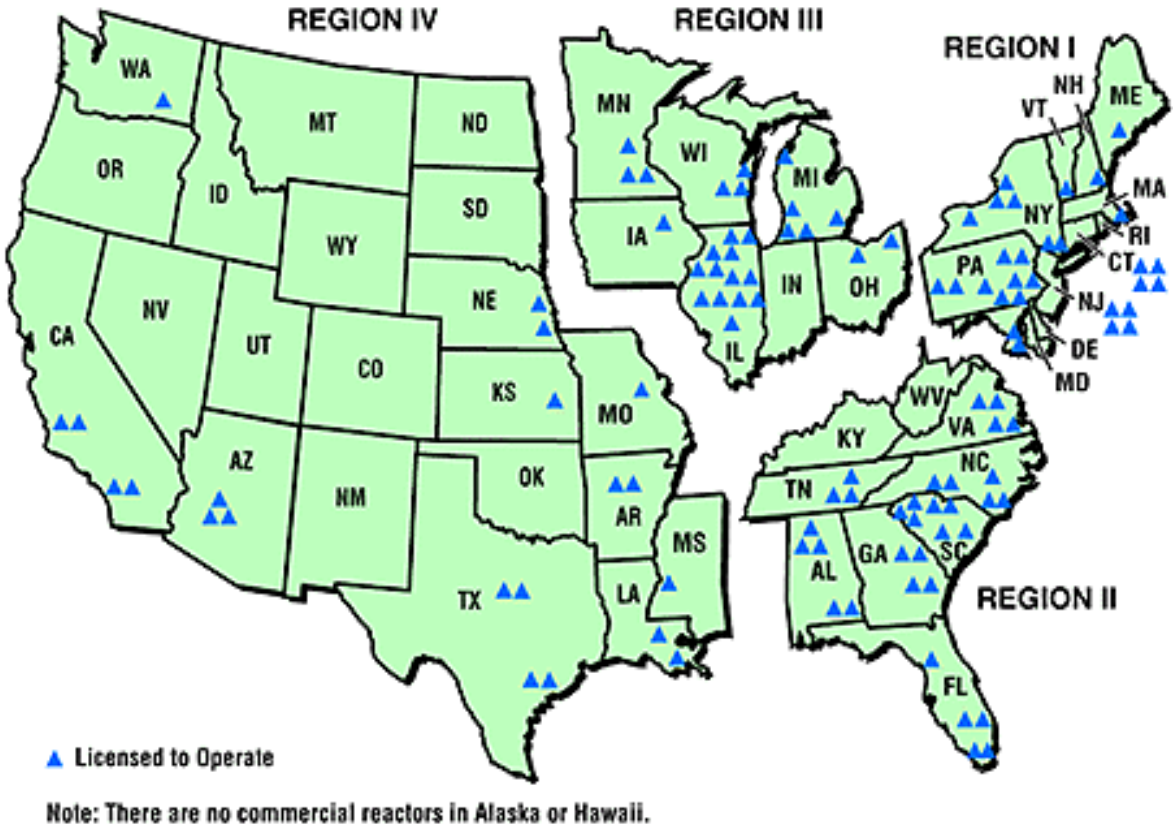

Figure 3: Nuclear Reactor Locations
(Source: U.S. NRC, 2008e)

Of these reactor sites, the first 35 alphabetically were chosen to be researched for this project to obtain a representative listing. The selected sites are shown in Figure 4. A complete listing of these reactor and county names is available in Appendix A. The number of states represented in our study is 23, with 5 located in Illinois. Many of the sites were located in the Midwest and on the east coast, with only two sites chosen west of the Rocky Mountains.

Figure 4: Reactor Sites Chosen for Research

One control county from each state containing a reactor was chosen (at random) for comparison purposes. A map of these control counties is shown in Figure 5, and a complete listing of county names is available in Appendix B. A total of 23 control counties were researched.

Figure 5: Control Counties for Each Chosen State

Community Water Systems

The Safe Drinking Water Information System (SDWIS) was used to generate a list of all active water systems within each county containing a chosen reactor site and within each control county. The data collected from each water system is presented in Appendices A and B. The information available includes:

1. The name of the reactor (if applicable)
2. The county and state in which it is located
3. The number of water systems in the county
4. The number of surface water systems
5. The number of groundwater systems
6. The number of systems with radionuclide violations
7. The number of systems with radionuclide MCL violations
8. The number of groundwater systems with radionuclide MCL violations
9. The number of surface water systems with radionuclide MCL violations
10. The number of systems with gross alpha radiation MCL violations
11. The number of systems with combined radium MCL violations

Hyperlinks to each of the water systems with any type of radionuclide violation are provided in Appendix C. This appendix also lists the type of system (groundwater or surface water), population served, and types of contaminants. A similar list for control systems is presented in Appendix D.

A total of 1,169 community water systems in the 35 counties with reactors were researched. Of these, 869 (74%) were groundwater systems and 300 (26%) were surface water systems. 116 systems had a radionuclide monitoring, reporting, and/or MCL violation, and 56 had MCL violations. Of these MCL violations, only 2 occurred in surface water systems. Of the 56 systems with MCL violations, 27 had gross alpha radiation violations, and 56 had combined radium violations. The total population affected by these MCL violations was 474,621.

Nearly all water systems near reactors that had MCL violations (51 of 56 or 91%) had more than one violation within the past ten years. Of the 56 systems with MCL violations, 11 were systems that served more than 5,000 people per system; however, these systems served 91% of the total population exposed to drinking water with at least one radionuclide MCL violation.

The control counties contained a total of 365 community water systems, of which 281 were groundwater systems and 84 were surface water systems. 11 water systems had some type of radionuclide violation, and 6 of these were MCL violations. All of these MCL violations occurred in groundwater systems. Of the 6 systems with MCL violations, all 6 had combined radium violations, and 2 had gross alpha violations. The total population affected by these MCL violations was 34,368. 4 of the 6 water systems with MCL violations had more than one MCL violation within the past ten years. 2 of the systems with MCL violations served more than 5,000 people, and these systems comprised 93% of the total affected population.

Table 29: Water System Comparison

		Systems		MCL Violations		Population Affected	
Location	Source Water	Number	Percentage	Number	Percentage	Number	Percentage
Near Reactors	Groundwater	869	74%	54	6.2%	443453	93%
	Surface Water	300	26%	2	0.67%	31168	7.0%
	Total	1169	100%	56	4.8%	474621	100%
Control	Groundwater	281	77%	6	2.1%	34368	100%
	Surface Water	84	23%	0	0%	0	0%
	Total	365	100%	6	1.6%	34368	100%

The data from counties with nuclear reactors were compared to the data from control counties using analysis of variance (ANOVA) conducted at the 95% confidence level. Statistical results are shown in Appendix E. First, analysis was conducted based on the occurrence of MCL violations using a binary data set (0 for no MCL violation in a water system; 1 for an MCL violation). Considering all water systems, there was a statistical difference in MCL occurrences between reactor counties and control counties (p-value = 0.008), with reactor counties having more occurrences. The same conclusion was reached when considering only groundwater systems (p-value = 0.007). However, there was no difference in MCL occurrences for surface water systems (p-value = 0.457).

Next, the data were analyzed based on quantitative values of the MCL violations. For gross alpha radiation, there was no statistical difference in the magnitude of MCL violations in reactor counties. P-values were 0.149, 0.170 and 0.464 for all systems, groundwater systems, and surface water systems, respectively. Similar conclusions were found for radium, with no statistical difference in the concentrations of radium in the reactor versus control counties (p-values ranged from 0.087 to 0.459).

Correlation Between MCL Violations and Cancer Rates

To attempt to determine if a correlation exists between the selected cancers and the dosage of radiation from drinking water (in pCi/L), the dosages were averaged by county for radium and gross alpha emissions, only systems that reported radionuclide concentrations were included. Then, each county was grouped into a radiation level. For radium, the groups were 0-5, 5-10, 10-15 and >15 pCi/L (MCL is 5 pCi/L). For gross alpha radiation, levels were 0-15, 15-

30, and >30 pCi/L (MCL is 15 pCi/L). Lastly, each county was assigned a cancer classification of "above", "similar to", or "below" in comparison to the national average for cancer rates by the State Cancer Profile system. This system was used to find whether or not a correlation exists between elevated radionuclide dosages and general cancer trends. The compiled data were compared using a single factor ANOVA analysis. Results are shown in Appendix F (cancer profiles) and appendix G (ANOVA results).

Stomach Cancer

A single factor ANOVA analysis of the collated stomach cancer data for radium was performed including 2 groups near reactors (5-10 and 10-15 pCi/L) and 4 groups in control counties (all 4 radium levels). There was no statistical difference between the sites near reactors and the control groups at a 95% confidence level. However the reported p-value was 0.053, which indicates that there was a difference at a 90% confidence interval. Elevated cancer rates were observed for the 10-15 pCi/L control county group and for the 15+ pCi/L control county group. However, elevated cancer rates were not observed at these radium levels in the reactor counties. Also, it is important to note that there was only one control county in the 10-15 pCi/L group. Thus, more data would be desirable to draw conclusions on stomach cancer rates.

A single factor ANOVA analysis of the collated stomach cancer data to gross alpha emissions was conducted. For the analysis there were six groups: 3 near reactors (0-15, 15-30, and >30 pCi/L gross alpha emissions) and 3 in control counties with the same ranges as the reactor counties. The analysis showed a difference between groups (p-value = 0.012). As with radium, elevated cancer rates were observed for 2 of the control counties, with alpha levels of 15-30 and >30 pCi/L. Again, there was only one county in each of these groups and levels were not significantly elevated in reactor counties with the same radionuclide levels. Thus, more data would be needed to substantiate these results.

General Cancer and Leukemia

Single factor ANOVA analyses were conducted for general cancer and leukemia data for both radium and gross alpha emissions. Six groups were established for each analysis, as described previously. In all cases, there were no statistical differences in cancer rates in the different groups.

Chapter 5: Conclusions and Recommendations

The following sections offer conclusions about the research done in this project as well as recommendations based on these findings. First, a discussion of the project's progression and results is given. Then, recommendations are given for future research done on this topic.

Conclusions

From the statistical analysis of the data gathered on community water systems, it can be concluded that living within the same county as a nuclear reactor does increase a person's risk of being exposed to radionuclide contaminated drinking water. This is based on analysis of MCL violations compared to control counties. In both the control counties and the counties with nuclear reactors, the majority of the violations occurred in groundwater systems (100% and 96%, respectively). These systems make up 100% of the population exposed to an MCL violation in the control group, and 93% of the affected population in the counties with reactors. However, statistical analysis showed no difference in the magnitude of MCL violations in the different counties.

Persons who live in a county with a nuclear reactor are at higher risk of being exposed to radionuclide contaminated drinking water via groundwater. However, we did not find a strong correlation between radionuclide contaminated drinking water and the risk of certain health conditions. There was no statistical evidence of an association between radium-, uranium- or radon-contaminated drinking water and stomach cancer, bladder cancer or kidney cancer for concentrations above the U.S. EPA MCLs. Two out of six leukemia/bone cancer studies found an association with radium concentrations below the U.S. EPA MCL. However, association between leukemia/bone cancer and uranium or radon concentrations at or above the U.S. EPA MCL was found. An association between the risk of tubular dysfunction (part of the renal system) and a uranium concentration of 300 to 1,920 μg/L in drinking water was found. This is substantially above the U.S. EPA MCL of 20 μg/L. However, there was no additional risk of glomerular dysfunction (part of the renal system) with this level of uranium concentration in drinking water. Finally, there was statistical evidence of risk of bone turnover in men associated with an increase of uranium concentration and drinking water.

Analysis of cancer rates in the studied counties compared to national cancer rates was conducted for radium and gross alpha emissions. A statistically different rate of stomach cancer

was found at certain levels of radionuclides in control counties. However, these elevated cancer rates were not found in reactor counties with the same levels of radionuclides. In addition, the database for this analysis was limited and in some cases there was only one county in a group. Also, no difference in general cancer or leukemia was noted at different radionuclide levels. A larger database is desirable to draw conclusions on cancer results.

In summary, we find that proximity to nuclear reactors does not significantly increase the risk of developing cancer.

Recommendations

Based on the case studies we reviewed, there may be a risk of developing leukemia/bone cancer at radium concentrations of 0.007 Bq/L (or 0.189 pCi/L) or higher in drinking water. More epidemiologic observational studies on radium contaminated drinking water and its possible effects on humans could be implemented. This would provide more evidence of whether or not a correlation between radium concentrations at these levels and any health risk exists. Since it is not certain if a correlation exists, the U.S. EPA should consider further investigation of the current MCL of 5 pCi/L.

To help reduce any possible risks to the public, the EPA could consider a combined radionuclide MCL, as opposed to solely individual constituents. There is precedence for this type of regulation. For example, trihalomethanes (a group of four potentially carcinogenic disinfection byproducts) are regulated as a group (MCL) and individually (MCLGs). This would take into consideration the cumulative effects of radionuclides.

Several recommendations can be made for future research into this topic. Due to time constraints, we were unable to research all counties containing a nuclear reactor; however, doing so would have yielded more complete results. If this is not possible, choosing the reactor sites to study by another method than alphabetically would allow for a larger geographical sampling. In addition, a larger control sample would grant a more statistically sound group for comparison to the collected data.

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Appendix A: Sites Near Nuclear Reactors

Reactor Name	County, State	Total Systems	Surface Water Systems	Ground-water Systems	Systems With Viola-tions	Systems With MCL Viola-tions	Ground-water Systems With MCL Violations	Surface Water Systems With MCL Viola-tions	Systems With Gross Alpha Viola-tions	Systems With Com-bined Radium Viola-tions
Arkansas Nuclear 1,2	Pope County, AR	9	9	0	0	0	0	0	0	0
Beaver 1,2	Allegheny, PA	41	38	3	5	0	0	0	0	0
Braid-wood 1,2	Will, IL	56	7	49	18	13	11	2	7	13
Brown's Ferry 1,2,3	Morgan, AL	6	6	0	0	0	0	0	0	0
Bruns-wick 1,2	Brunswick, NC	15	13	2	0	0	0	0	0	0
Byron 1,2	Winnebago, IL	33	0	33	7	7	7	0	1	7
Callaway	Callaway, MO	14	0	14	5	1	1	0	1	1
Calvert Cliffs 1,2	Calvert, MD	35	0	35	0	0	0	0	0	0
Catawba 1,2	York, SC	72	13	59	1	1	1	0	1	0
Clinton	DeWitt, IL	8	0	8	0	0	0	0	0	0
Colum-bia Generat-ing Station	Benton, WA	39	4	35	0	0	0	0	0	0
Coman-che Peak 1,2	Somervelle, TX	8	0	8	0	0	0	0	0	0
Cooper	Nemaha, NE	9	0	9	0	0	0	0	0	0
Crystal River 3	Citrus, FL	62	0	62	0	0	0	0	0	0
D.C. Cook 1,2	Berrien, MI	45	12	33	1	0	0	0	0	0
Davis-Besse	Ottawa, OH	11	7	4	1	0	0	0	0	0
Diablo Canyon 1,2	San Luis Obispo, CA	67	19	48	0	0	0	0	0	0
Dresden 2,3	Grundy, IL	19	0	19	10	7	7	0	6	7
Duane Arnold	Linn, IA	47	4	43	9	1	1	0	0	1
Farley 1,2	Houston, AL	11	0	11	1	0	0	0	0	0
Fermi 2	Monroe, OH	6	2	4	2	0	0	0	0	0
Fitz-Patrick	Oswego, NY	66	21	45	0	0	0	0	0	0
Fort	Washington,	12	7	5	0	0	0	0	0	0

Calhoun	NE									
Ginna	Wayne, NY	47	42	5	1	0	0	0	0	0
Grand Gulf 1	Claiborne, MS	7	0	7	0	0	0	0	0	0
Hatch 1,2	Appling, GA	5	0	5	0	0	0	0	0	0
Hope Creek 1	Salem, NJ	15	1	14	1	1	1	0	0	1
Indian Point 2,3	Westchester, NY	94	47	47	5	2	2	0	2	1
Kewau-nee	Kewaunee, WI	4	0	4	0	0	0	0	0	0
La Salle 1,2	La Salle, IL	38	1	37	20	19	19	0	7	19
Limerick 1,2	Montgomery, PA	38	11	27	11	0	0	0	0	0
McGuire 1,2	Mecklenburg, NC	37	1	36	4	2	2	0	1	1
Mill-stone 2,3	New London, CT	107	14	93	13	1	1	0	1	1
Monti-cello	Wright, MN	20	0	20	1	1	1	0	0	1
Nine Mile Point 1,2	Oswego, NY	66	21	45	0	0	0	0	0	0

Appendix B: Control Counties

County, State	Total Systems	Surface Water Systems	Groundwater Systems	Systems With Violations	Systems With MCL Violations	Groundwater Systems With MCL Violations	Surface Water Systems With MCL Violations	Systems With Gross Alpha Violations	Systems With Combined Radium Violations
Kendall, IL	9	0	9	4	4	4	0	2	4
Marshall, IA	14	1	13	1	1	1	0	0	1
Columbus, NC	18	4	14	1	0	0	0	0	0
New Haven, CT	40	11	29	5	1	1	0	0	1
Clay, MO	21	8	13	0	0	0	0	0	0
Marion, SC	5	1	4	0	0	0	0	0	0
Camden, NJ	24	3	21	0	0	0	0	0	0
Lewis, NY	18	9	9	0	0	0	0	0	0
Hubbard, MN	6	0	6	0	0	0	0	0	0
Walla Walla, WA	32	3	29	0	0	0	0	0	0
Merced, CA	23	2	21	0	0	0	0	0	0
Ellis, TX	31	10	21	0	0	0	0	0	0
Burt, NE	6	0	6	0	0	0	0	0	0
Woodruff, AR	7	0	7	0	0	0	0	0	0
Stone, MS	8	0	8	0	0	0	0	0	0
Price, WI	5	0	5	0	0	0	0	0	0
Mason, MI	9	3	6	0	0	0	0	0	0
Miami, OH	17	1	16	0	0	0	0	0	0
Huntingdon, PA	20	7	13	0	0	0	0	0	0
Allegany, MD	27	21	6	0	0	0	0	0	0
Crisp, GA	13	0	13	0	0	0	0	0	0
Indian River, FL	5	0	5	0	0	0	0	0	0
Coffee, AL	7	0	7	0	0	0	0	0	0

Appendix C: Hyperlinks to Water Systems Near Nuclear Reactors

Beaver 1,2:
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=PA5020010&state=PA&source=Groundwater&population=6133&sys_num=0
0 MCLs
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=PA5020011&state=PA&source=Surface_water&population=19922&sys_num=0
0 MCLs
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=PA5020039&state=PA&source=Surface_water&population=660000&sys_num=0
0 MCLs
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=PA5020038&state=PA&source=Surface_water&population=250000&sys_num=0
0 MCLs
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=PA5020055&state=PA&source=Surface_water&population=4700&sys_num=0
0 MCLs

Braidwood 1,2:
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL1977210&state=IL&source=Purch_groundwater&population=309&sys_num=0
Groundwater, pop=309, Radium, Alpha
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL1970150&state=IL&source=Groundwater&population=5203&sys_num=0
0 MCLs
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL1970200&state=IL&source=Groundwater&population=8967&sys_num=0
Groundwater, pop=8967, Radium
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL1970070&state=IL&source=Purch_groundwater&population=561&sys_num=0
Groundwater, pop=561, Radium, Alpha
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL1975105&state=IL&source=Groundwater&population=146&sys_num=0
0 MCLs
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL1970350&state=IL&source=Groundwater&population=1450&sys_num=0
0 MCLs
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL1970450&state=IL&source=Groundwater&population=106221&sys_num=0
Groundwater, pop=106221, Radium, Alpha
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL1977940&state=IL&source=Groundwater&population=210&sys_num=0
Groundwater, pop=210, Radium
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL1975930&state=IL&source=Purch_surface_water&population=868&sys_num=0
Surface Water, pop=868, Radium, Alpha
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL1970500&state=IL&source=Groundwater&population=23403&sys_num=0
Groundwater, pop=23403, Radium, Alpha
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL1978100&state=IL&source=Groundwater&population=2706&sys_num=0
0 MCLs
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL1970550&state=IL&source=Groundwater&population=5768&sys_num=0
Groundwater, pop=5768, Radium
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL1970800&state=IL&source=Purch_surface_water&population=30300&sys_num=0
Surface Water, pop=30300, Radium, Alpha
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL1977650&state=IL&source=Groundwater&population=250&sys_num=0

0 MCLs
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL1970850&state=IL&source=Groundwater&population=1888&sys_num=0
Groundwater, pop=1888, Radium
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL1970900&state=IL&source=Groundwater&population=50001&sys_num=0
Groundwater, pop=50001, Radium, Alpha
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL1977910&state=IL&source=Purch_groundwater&population=2850&sys_num=0
Groundwater, pop=2850, Radium
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL1975200&state=IL&source=Groundwater&population=749&sys_num=0
Groundwater, pop=749, Radium

Byron 1,2:
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL2015495&state=IL&source=Groundwater&population=970&sys_num=0
Groundwater, pop=970, Radium
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL2015488&state=IL&source=Groundwater&population=1816&sys_num=0
Groundwater, pop=1816, Radium
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL2010450&state=IL&source=Purch_groundwater&population=4700&sys_num=0
Groundwater, pop=4700, Radium
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL2010150&state=IL&source=Groundwater&population=22476&sys_num=0
Groundwater, pop=22476, Radium
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL2010300&state=IL&source=Groundwater&population=155000&sys_num=0
Groundwater, pop=155000, Radium, Alpha
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL2010350&state=IL&source=Groundwater&population=7440&sys_num=0
Groundwater, pop=7440, Radium
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL2015160&state=IL&source=Groundwater&population=388&sys_num=0
Groundwater, pop=388, Radium

Callaway:
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=MO3024085&state=MO&source=Groundwater&population=13500&sys_num=0
0 MCLs
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=MO3069004&state=MO&source=Groundwater&population=2005&sys_num=0
0 MCLs
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=MO3010424&state=MO&source=Groundwater&population=162&sys_num=0
0 MCLs
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=MO3048994&state=MO&source=Groundwater&population=87&sys_num=0
Groundwater, pop=87, Radium, Alpha
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=MO3048263&state=MO&source=Groundwater&population=67&sys_num=0
0 MCLs
Catawba:
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=SC4650008&state=SC&source=Groundwater&population=420&sys_num=0
Groundwater, pop=420, Alpha

D.C. Cook 1,2:
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=MI0005625&state=MI&source=Groundwater&population=188&sys_num=0
0 MCLs

Davis-Besse:
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=OH6204112&state=OH&source=Groundwater&population=100&sys_num=0
0 MCLs

Dresden 2,3:
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL0630050&state=IL&source=Groundwater&population=792&sys_num=0
0 MCLs
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL0630100&state=IL&source=Purch_groundwater&population=392&sys_num=0
Groundwater, pop=392, Radium, Alpha
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL0630250&state=IL&source=Groundwater&population=2300&sys_num=0
Groundwater, pop=2300, Radium, Alpha
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL0630400&state=IL&source=Groundwater&population=1406&sys_num=0
Groundwater, pop=1406, Radium, Alpha
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL0630450&state=IL&source=Groundwater&population=112&sys_num=0
Groundwater, pop=112, Radium, Alpha
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL0630550&state=IL&source=Groundwater&population=7695&sys_num=0
0 MCLs
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL0630600&state=IL&source=Groundwater&population=11928&sys_num=0
0 MCLs
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL0630060&state=IL&source=Groundwater&population=99&sys_num=0
Groundwater, pop=99, Radium, Alpha
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL0635225&state=IL&source=Groundwater&population=730&sys_num=0
Groundwater, pop=730, Radium
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL0630650&state=IL&source=Groundwater&population=621&sys_num=0
Groundwater, pop=621, Radium, Alpha

Duane Arnold:
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IA5784309&state=IA&source=Groundwater&population=80&sys_num=0
0 MCLs
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IA5784307&state=IA&source=Groundwater&population=228&sys_num=0
0 MCLs
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IA5784314&state=IA&source=Groundwater&population=142&sys_num=0
0 MCLs
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IA5731032&state=IA&source=Groundwater&population=1662&sys_num=0
0 MCLs
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IA5784313&state=IA&source=Groundwater&population=88&sys_num=0
0 MCLs
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IA5784302&state=IA&source=Groundwater&population=72&sys_num=0
0 MCLs
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IA5758021&state=IA&source=Groundwater&population=4171&sys_num=0
0 MCLs

http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IA5784311&state=IA&source=Groundwater&population=154&sys_num=0
0 MCLs
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IA5765302&state=IA&source=Groundwater&population=45&sys_num=0
Groundwater, pop=45, Radium

Farley 1,2:
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=AL0000671&state=AL&source=Groundwater&population=2934&sys_num=0
0 MCLs

Fermi 2:
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=OH5600012&state=OH&source=Groundwater&population=440&sys_num=0
0 MCLs
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=OH5600812&state=OH&source=Groundwater&population=4258&sys_num=0
0 MCLs

Ginna:
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=NY5800674&state=NY&source=Groundwater&population=105&sys_num=0
0 MCLs

Hope Creek 1:
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=NJ1710001&state=NJ&source=Groundwater&population=960&sys_num=0
Groundwater, pop=960, Radium

Indian Point 2,3:
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=NY5903424&state=NY&source=Groundwater&population=175&sys_num=0
Groundwater, pop=175, Radium, Alpha
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=NY5930031&state=NY&source=Groundwater&population=400&sys_num=0
0 MCLs
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=NY5916740&state=NY&source=Groundwater&population=45&sys_num=0
0 MCLs
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=NY5903154&state=NY&source=Groundwater&population=650&sys_num=0
0 MCLs
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=NY5930049&state=NY&source=Groundwater&population=224&sys_num=0
Groundwater, pop=224, Alpha

La Salle 1,2:
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL0995040&state=IL&source=Groundwater&population=275&sys_num=0
Groundwater, pop=275, Radium
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL0995365&state=IL&source=Groundwater&population=295&sys_num=0
Groundwater, pop=295, Radium, Alpha
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL0995150&state=IL&source=Purch_groundwater&population=312&sys_num=0
Groundwater, pop=312, Radium, Alpha
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL0990060&state=IL&source=Groundwater&population=150&sys_num=0
Groundwater, pop=150, Radium, Alpha
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL0995300&state=IL&source=Groundwater&population=70&sys_num=0

Groundwater, pop=70, Radium, Alpha
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL0995329&state=IL&source=Groundwater&population=155&sys_num=0
Groundwater, pop=155, Radium
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL0990450&state=IL&source=Groundwater&population=486&sys_num=0
Groundwater, pop=486, Radium, Alpha
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL0995336&state=IL&source=Groundwater&population=110&sys_num=0
Groundwater, pop=110, Radium
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL0990500&state=IL&source=Groundwater&population=4655&sys_num=0
Groundwater, pop=4655, Radium
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL0990110&state=IL&source=Groundwater&population=85&sys_num=0
Groundwater, pop=85, Radium
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL0990550&state=IL&source=Groundwater&population=7272&sys_num=0
Groundwater, pop=7272, Radium
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL0990600&state=IL&source=Groundwater&population=620&sys_num=0
Groundwater, pop=620, Radium
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL0990650&state=IL&source=Groundwater&population=1105&sys_num=0
Groundwater, pop=1105, Radium
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL0995250&state=IL&source=Groundwater&population=60&sys_num=0
0 MCLs
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL0990700&state=IL&source=Groundwater&population=4000&sys_num=0
Groundwater, pop=4000, Radium
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL0990800&state=IL&source=Groundwater&population=18307&sys_num=0
Groundwater, pop=18307, Radium, Alpha
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL0990900&state=IL&source=Groundwater&population=483&sys_num=0
Groundwater, pop=483, Radium
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL0995400&state=IL&source=Purch_groundwater&population=220&sys_num=0
Groundwater, pop=220, Radium, Alpha
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL0991050&state=IL&source=Groundwater&population=2053&sys_num=0
Groundwater, pop=2053, Radium
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL0995425&state=IL&source=Groundwater&population=73&sys_num=0
Groundwater, pop=73, Radium

Limerick 1,2:
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=PA1460055&state=PA&source=Groundwater&population=8800&sys_num=0
0 MCLs
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=PA1460075&state=PA&source=Groundwater&population=300&sys_num=0
0 MCLs
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=PA1460034&state=PA&source=Purch_surface_water&population=74287&sys_num=0
0 MCLs
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=PA1460030&state=PA&source=Groundwater&population=130&sys_num=0
0 MCLs
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=PA1460008&state=PA&source=Groundwater&population=1300&sys_num=0

0 MCLs
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=PA1460087&state=PA&source=Groundwater&population=508&sys_num=0
0 MCLs
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=PA1460006&state=PA&source=Groundwater&population=45&sys_num=0
0 MCLs
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=PA1460038&state=PA&source=Groundwater&population=220&sys_num=0
0 MCLs
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=PA1460085&state=PA&source=Groundwater&population=7500&sys_num=0
0 MCLs
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=PA1460005&state=PA&source=Groundwater&population=112&sys_num=0
0 MCLs
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=PA1460064&state=PA&source=Groundwater&population=175&sys_num=0
0 MCLs

McGuire 1,2:
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=NC0160230&state=NC&source=Groundwater&population=163&sys_num=0
0 MCLs
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=NC0160253&state=NC&source=Groundwater&population=394&sys_num=0
Groundwater, pop=394, Alpha
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=NC0160379&state=NC&source=Groundwater&population=76&sys_num=0
0 MCLs
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=NC2060052&state=NC&source=Groundwater&population=259&sys_num=0
Groundwater, pop=259, Radium

Millstone 2,3:
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=CT1051011&state=CT&source=Groundwater&population=28&sys_num=0
0 MCLs
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=CT0710011&state=CT&source=Groundwater&population=172&sys_num=0
0 MCLs
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=CT0721041&state=CT&source=Groundwater&population=47&sys_num=0
0 MCLs
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=CT0450011&state=CT&source=Groundwater&population=15245&sys_num=0
0 MCLs
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=CT0580021&state=CT&source=Groundwater&population=186&sys_num=0
Groundwater, pop=186, Radium, Alpha
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=CT0860091&state=CT&source=Groundwater&population=72&sys_num=0
0 MCLs
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=CT0727061&state=CT&source=Groundwater&population=220&sys_num=0
0 MCLs
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=CT1140021&state=CT&source=Groundwater&population=80&sys_num=0
0 MCLs
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=CT0730031&state=CT&source=Groundwater&population=155&sys_num=0
0 MCLs

http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=CT1051021&state=CT&source=Groundwater&population=440&sys_num=0
0 MCLs
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=CT1056241&state=CT&source=Groundwater&population=78&sys_num=0
0 MCLs
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=CT1040091&state=CT&source=Groundwater&population=306&sys_num=0
0 MCLs
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=CT0598011&state=CT&source=Groundwater&population=164&sys_num=0
0 MCLs

Monticello:
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=MN1860008&state=MN&source=Groundwater&population=600&sys_num=0
Groundwater, pop=600, Radium

Appendix D: Hyperlinks to Control Water Systems

Kendall, IL
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL0935150&state=IL&source=Groundwater&population=273&sys_num=0
Groundwater, pop=273, Radium
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL0935140&state=IL&source=Groundwater&population=66&sys_num=0
Groundwater, pop=66, Radium
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL0930150&state=IL&source=Groundwater&population=25855&sys_num=0
Groundwater, pop=25855, Radium, Alpha
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IL0930250&state=IL&source=Groundwater&population=6189&sys_num=0
Groundwater, pop=6189, Radium, Alpha

Marshall, IA
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=IA6484093&state=IA&source=Groundwater&population=1349&sys_num=0
Groundwater, pop=1349, Radium

Columbus, NC
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=NC0424015&state=NC&source=Purch_surface_water&population=3175&sys_num=0
0 MCLs

New Haven, CT
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=CT1300031&state=CT&source=Groundwater&population=636&sys_num=0
Groundwater, pop=636, Radium
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=CT0020021&state=CT&source=Purch_surface_water&population=29600&sys_num=0
0 MCLs
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=CT1662051&state=CT&source=Groundwater&population=218&sys_num=0
0 MCLs
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=CT0608011&state=CT&source=Surface_water&population=33143&sys_num=0
0 MCLs
http://oaspub.epa.gov/enviro/sdw_report_v2.first_table?pws_id=CT0765101&state=CT&source=Groundwater&population=270&sys_num=0
0 MCLs

Appendix E: ANOVA Analysis of Water System Data

MCL Occurrences:

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Total Ctrl	364	6	0.016484	0.016256
Total Near	1169	56	0.047904	0.045648

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.274034	1	0.274034	7.084722	0.007856	3.84754
Within Groups	59.21846	1531	0.03868			
Total	59.4925	1532				

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
GW Near	869	54	0.06214	0.058346
GW Ctrl	281	6	0.021352	0.020971

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.35326	1	0.35326	7.175677	0.007495	3.849572
Within Groups	56.5163	1148	0.04923			
Total	56.86957	1149				

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
SW Near	300	2	0.006667	0.006644
SW Ctrl	83	0	0	0

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.002889	1	0.002889	0.554138	0.457091	3.865981
Within Groups	1.986667	381	0.005214			
Total	1.989556	382				

Alpha MCL Violations:

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Total Ctrl	364	86.25	0.236951	7.838968
Total Near	1169	633.05	0.541531	13.78407

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	25.75007	1	25.75007	2.0809	0.149357	3.84754
Within Groups	18945.34	1531	12.37449			
Total	18971.09	1532				

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
GW Near	869	591.05	0.68015	17.43561
GW Ctrl	281	86.25	0.30694	10.1411

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	29.5757	1	29.5757	1.889041	0.169578	3.849572
Within Groups	17973.62	1148	15.65646			
Total	18003.19	1149				

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
SW Near	300	42	0.14	3.012107
SW Ctrl	83	0	0	0

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	1.274256	1	1.274256	0.539064	0.463273	3.865981
Within Groups	900.62	381	2.363832			
Total	901.8943	382				

Radium MCL Violations:

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Total Ctrl	364	82.534	0.226742	4.530717
Total Near	1169	532.546	0.455557	5.102416

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	14.5326	1	14.5326	2.925908	0.087371	3.84754
Within Groups	7604.272	1531	4.966866			
Total	7618.805	1532				

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
GW Ctrl	281	82.534	0.293715	5.85401
GW Near	869	509.166	0.585922	6.484497

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*

Between Groups	18.13042	1	18.13042	2.86388	0.09086	3.849572
Within Groups	7267.666	1148	6.330719			
Total	7285.796	1149				

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
SW Near	300	23.38	0.077933	0.914817
SW Ctrl	83	0	0	0

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.394864	1	0.394864	0.550005	0.458773	3.865981
Within Groups	273.5303	381	0.717927			
Total	273.9252	382				

Appendix F: Cancer Profiles

Cancer Rate (deaths per 100,000 people)

	Location	Radium Level	Stomach Cancer	General Cancers	Leukemia
	Near Reactors				
10-15 pCi/L	Westchester, NY	1.357E+01	5.2	175.3	7.7
	Grundy, IL	1.262E+01	n/a	209	14.9
	New London, CT	1.130E+01	3.8	194.8	7.4
	Will, IL	1.108E+01	4.3	197.9	9
5-10 pCi/L	La Salle, IL	9.613E+00	2.5	213.3	7.1
	Salem, NJ	7.370E+00	n/a	227	7.9
	Winnebago, IL	6.815E+00	4.6	205.6	6.9
	Linn, IA	6.300E+00	3.5	186	8.4
	Mecklenburg, NC	6.000E+00	4	186.1	7.1
	Wright, MN	5.900E+00	n/a	178.4	10.1
	Callaway, MO	5.800E+00	n/a	212.5	n/a
	Control sites				
15+ pCi/L	NEW HAVEN, CT	3.335E+01	4.9	194	7.3
10-15 pCi/L	KENDALL, IL	1.052E+01	6.9	194.5	n/a
5-10 pCi/L	MARSHALL, IA	7.100E+00	n/a	212.4	10.6
0-5 pCi/L	CLAY, MO	No Violations	3.5	198.8	9.6
	MARION, SC	No Violations	n/a	231.6	n/a
	CAMDEN, NJ	No Violations	5	218	7.5
	LEWIS, NY	No Violations	n/a	198.8	11
	COLUMBUS, NC	No Violations	6.2	212.9	9.6
	HUBBARD, MN	No Violations	n/a	167.8	n/a
	WALLA WALLA, WA	No Violations	n/a	169.9	8.1
	MERCED, CA	No Violations	5	180	9
	ELLIS, TX	No Violations	n/a	216	8.8
	BURT, NE	No Violations	n/a	190.1	n/a
	WOODRUFF, AR	No Violations	n/a	276	n/a
	STONE, MS	No Violations	n/a	257.7	n/a
	PRICE, WI	No Violations	n/a	175.1	n/a

	MASON, MI	No Violations	n/a	215.9	n/a
	MIAMI, OH	No Violations	n/a	187.2	9.3
	HUNTINGDON, PA	No Violations	n/a	180.4	9.4
	ALLEGANY, MD	No Violations	n/a	194.8	5.6
	CRISP, GA	No Violations	n/a	211.8	n/a
	INDIAN RIVER, FL	No Violations	2.8	185.6	7.6
	COFFEE, AL	No Violations	6.6	216.7	n/a

USA	X	4.2	192.7	7.5

Average Dosages			
"above" average pCi/L	4.773E+01	7.370E+00	3.721E+01
"Similar to" average pCi/L	2.863E+01	3.027E+01	2.735E+01
"Below"/"unavailable average" pCi/L	1.836E+01		2.795E+01

Above, similar to, and below were determined by the State Cancer Profile System and are a comparison to the national average for death rate.
(National Cancer Institute, 2008)

Cancer Rate (deaths per 100,000 people)

	Location	Gross Alpha	Stomach Cancer	General Cancers	Leukemia
	Near Reactors				
30+ pCi/L	Mecklenburg, NC	3.645E+01	4	186.1	7.1
15-30 pCi/L	Grundy, IL	2.641E+01	n/a	209	14.9
	Will, IL	2.431E+01	4.3	197.9	9
	La Salle, IL	2.276E+01	2.5	213.3	7.1
	New London, CT	2.170E+01	3.8	194.8	7.4
	Westchester, NY	2.049E+01	5.2	175.3	7.7
	Callaway, MO	1.858E+01	n/a	212.5	n/a
	Winnebago, IL	1.733E+01	4.6	205.6	6.9
0-15 pCi/L	Salem, NJ	No Violations	n/a	227	7.9
	Linn, IA	No Violations	3.5	186	8.4
	Wright, MN	No Violations	n/a	178.4	10.1
	Control sites				
30+ pCi/L	NEW HAVEN, CT	4.425E+01	4.9	194	7.3
15-30 pCi/L	KENDALL, IL	2.100E+01	6.9	194.5	n/a
0-15 pCi/L	MARSHALL, IA	No Violations	n/a	212.4	10.6
	CLAY, MO	No Violations	3.5	198.8	9.6
	MARION, SC	No Violations	n/a	231.6	n/a
	CAMDEN, NJ	No Violations	5	218	7.5
	LEWIS, NY	No Violations	n/a	198.8	11
	COLUMBUS, NC	No Violations	6.2	212.9	9.6
	HUBBARD, MN	No Violations	n/a	167.8	n/a
	WALLA WALLA, WA	No Violations	n/a	169.9	8.1
	MERCED, CA	No Violations	5	180	9
	ELLIS, TX	No Violations	n/a	216	8.8
	BURT, NE	No Violations	n/a	190.1	n/a
	WOODRUFF, AR	No Violations	n/a	276	n/a
	STONE, MS	No Violations	n/a	257.7	n/a

	PRICE, WI	No Violations	n/a	175.1	n/a
	MASON, MI	No Violations	n/a	215.9	n/a
	MIAMI, OH	No Violations	n/a	187.2	9.3
	HUNTINGDON, PA	No Violations	n/a	180.4	9.4
	ALLEGANY, MD	No Violations	n/a	194.8	5.6
	CRISP, GA	No Violations	n/a	211.8	n/a
	INDIAN RIVER, FL	No Violations	2.8	185.6	7.6
	COFFEE, AL	No Violations	6.6	216.7	n/a

USA	X	4.2	192.7	7.5

Average Dosages			
"above" average pCi/L	4.773E+01	7.370E+00	3.721E+01
"Similar to" average pCi/L	2.863E+01	3.027E+01	2.735E+01
"Below"/"unavailable average" pCi/L	1.836E+01		2.795E+01

Above, similar to, and below were determined by the State Cancer Profile System and are a comparison to the national average for death rate.
(National Cancer Institute, 2008)

Appendix G: Statistical Analysis of Cancer Rates

Radium

	Near Reactors			Control		
Group	NR10-15 pCi/L	NR5-10 pCi/L	C15+ pCi/L	C10-15 pCi/L	C5-10 pCi/L	C0-5 pCi/L
General Cancer	175.3	213.3	194	194.5	212.4	198.8
	209	227				231.6
	194.8	205.6				218
	197.9	186				198.8
		186.1				212.9
		178.4				167.8
		212.5				169.9
						180
						216
						190.1
						276
						257.7
						175.1
						215.9
						187.2
						180.4
						194.8
						211.8
						185.6
						216.7
Stomach Cancer	10-15 pCi/L	5-10 pCi/L	15+ pCi/L	10-15 pCi/L	5-10 pCi/L	0-5 pCi/L
	5.2	2.5	4.9	6.9	3	3.5
	3	3				3
	3.8	4.6				5
	4.3	3.5				3
		4				6.2
		3				3
		3				3
						5
						3
						3
						3
						3
						3
						3
						3
						2.8
						6.6
Leukemia	10-15 pCi/L	5-10 pCi/L	15+ pCi/L	10-15 pCi/L	5-10 pCi/L	0-5 pCi/L
	7.7	7.1	7.3	3	10.6	9.6
	14.9	7.9				3
	7.4	6.9				7.5
	9	8.4				11
		7.1				9.6
		10.1				3
		3				8.1
						9
						8.8
						3
						3
						3
						3
						9.3
						9.4
						5.6
						3
						7.6
						3

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
NR10-15 pCi/L	4	777	194.25	196.7633333
NR5-10 pCi/L	7	1408.9	201.2714286	322.992381
C15+ pCi/L	1	194	194	#DIV/0!
C10-15 pCi/L	1	194.5	194.5	#DIV/0!
C5-10 pCi/L	1	212.4	212.4	#DIV/0!
C0-5 pCi/L	20	4085.1	204.255	789.7499737

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	573.6288613	5	114.7257723	0.183210583	0.96660482	2.558127499
Within Groups	17533.49379	28	626.1962066			
Total	18107.12265	33				

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
10-15 pCi/L	4	16.3	4.075	0.849166667
5-10 pCi/L	7	23.6	3.371428571	0.515714286
15+ pCi/L	1	4.9	4.9	#DIV/0!
10-15 pCi/L	1	6.9	6.9	#DIV/0!
5-10 pCi/L	1	3	3	#DIV/0!
0-5 pCi/L	20	71.1	3.555	1.333131579

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	13.90871429	5	2.781742857	2.514871379	0.053105509	2.558127499
Within Groups	30.97128571	28	1.106117347			
Total	44.88	33				

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
10-15 pCi/L	4	39	9.75	12.27
5-10 pCi/L	7	50.5	7.214285714	4.681428571
15+ pCi/L	1	7.3	7.3	#DIV/0!
10-15 pCi/L	1	3	3	#DIV/0!
5-10 pCi/L	1	10.6	10.6	#DIV/0!
0-5 pCi/L	20	122.5	6.125	9.488289474

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	74.16892857	5	14.83378571	1.694072336	0.168775414	2.558127499
Within Groups	245.1760714	28	8.756288265			
Total	319.345	33				

Gross Alpha

	Near Reactors			Control		
Group	30+ pCi/L	15-30 pCi/L	0-15 pCi/L	30+ pCi/L	15-30 pCi/L	0-15 pCi/L
General Cancer	186.1	209	227	194	194.5	212.4
		197.9	186			198.8
		213.3	178.4			231.6
		194.8				218
		175.3				198.8
		212.5				212.9
		205.6				167.8
						169.9
						180
						216
						190.1
						276
						257.7
						175.1
						215.9
						187.2
						180.4
						194.8
						211.8
						185.6
						216.7
Stomach Cancer	30+ pCi/L	15-30 pCi/L	0-15 pCi/L	30+ pCi/L	15-30 pCi/L	0-15 pCi/L
	4	3	3	4.9	6.9	3
		4.3	3.5			3.5
		2.5	3			3
		3.8				5
		5.2				3
		3				6.2
		4.6				3
						3
						5
						3
						3
						3
						3
						3
						3
						3
						3
						2.8
Leukemia	30+ pCi/L	15-30 pCi/L	0-15 pCi/L	30+ pCi/L	15-30 pCi/L	0-15 pCi/L
	7.1	14.9	7.9	7.3	3	10.6
		9	8.4			9.6
		7.1	10.1			3
		7.4				7.5
		7.7				11
		3				9.6
		6.9				3
						8.1
						9
						8.8
						3
						3
						3
						3
						9.3
						9.4
						5.6
						3
						7.6
						3

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
30+ pCi/L	1	186.1	186.1	#DIV/0!
15-30 pCi/L	7	1408.4	201.2	179.4933333
0-15 pCi/L	3	591.4	197.1333333	683.4533333
30+ pCi/L	1	194	194	#DIV/0!
15-30 pCi/L	1	194.5	194.5	#DIV/0!
0-15 pCi/L	21	4297.5	204.6428571	753.4215714

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	594.8245518	5	118.9649104	0.190210187	0.963827848	2.558127499
Within Groups	17512.2981	28	625.4392177			
Total	18107.12265	33				

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
30+ pCi/L	1	4	4	#DIV/0!
15-30 pCi/L	7	26.4	3.771428571	0.969047619
0-15 pCi/L	3	9.5	3.166666667	0.083333333
30+ pCi/L	1	4.9	4.9	#DIV/0!
15-30 pCi/L	1	6.9	6.9	#DIV/0!
0-15 pCi/L	20	67.5	3.375	0.827236842

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	14.51669913	5	2.903339827	3.61270813	0.012466816	2.571886404
Within Groups	21.69845238	27	0.803646384			
Total	36.21515152	32				

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
30+ pCi/L	1	7.1	7.1	#DIV/0!
15-30 pCi/L	7	56	8	12.68
0-15 pCi/L	3	26.4	8.8	1.33
30+ pCi/L	1	7.3	7.3	#DIV/0!
15-30 pCi/L	1	3	3	#DIV/0!
0-15 pCi/L	21	133.1	6.338095238	9.96747619

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	41.25547619	5	8.251095238	0.83077803	0.538782235	2.558127499
Within Groups	278.0895238	28	9.931768707			
Total	319.345	33				